THERMAL RESPONSE OF UHMWPE MATERIALS IN A FLASH FLAME TEST ENVIRONMENT

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14. ABSTRACT
Despite excellent ballistic protection properties, Ultra High Molecular Weight Polyethylene (UHMWPE) material has generally not been considered for certain applications in protective apparel due to its low melting point. This report describes a research effort to test UHMWPE fabric and composite material in a flash flame environment when protected by a flame-resistant (FR) fabric outer layer. This research was funded and managed through a US Army science and technology program Technology Enabled Capability Demonstration (TeCD): Force Protection Soldier and Small Unit. Testing was conducted at the Natick Soldier Research, Development and Engineering Center (NSRDEC) Ouellette Thermal Test Facility in accordance with the ASTM F1930 Standard Test Method for Evaluation of Flame Resistant Clothing for Protection Against Fire Simulations Using an Instrumented Manikin. Several UHMWPE fabrics were tested underneath an FR fabric outer layer of Tencate Defender M. Prior to fabricating test garments, preliminary flash flame testing was conducted with a midscale test setup, which guided the full-scale thermal manikin test plan. Test garments were fabricated for evaluation on the instrumented thermal test manikin, which included the UHMWPE undergarments (shorts and vest) and an FR fabric coverall as well as the FR Army Combat Uniform (FRACU). All tests were conducted according to ASTM F1930 with a 4-s flame duration calibrated to 84 kW/m^2. The UHMWPE undergarments remained intact after all of the flash flame tests. Some distortion of the UHMWPE fabric was observed in localized areas. No melt/drip response was observed in the FR fabric shielded UHMWPE undergarments, and they provided a similar reduction in transmitted heat flux as was measured in tests with cotton undergarments.

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SAFETY, HEAT FLUX, FLAMMABILITY, FLAME RETARDANT, FLAMES, MANNEQUINS, BURNS(INJURIES), PROTECTIVE CLOTHING, COTTON, FLASH FLAMES, UNDERGARMENTS, TEST AND EVALUATION, FABRICS, FLAME TESTING, FIRE PROTECTION, FIRE RESISTANT TEXTILES, UHMWPE(ULTRA HIGH MOLECULAR WEIGHT POLYETHYLENE)

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THERMAL RESPONSE OF UHMWPE MATERIALS IN A FLASH FLAME TEST ENVIRONMENT

1 Introduction

This report describes a research effort, conducted from October 2012 to April 2014, to test Ultra High Molecular Weight Polyethylene (UHMWPE) fabric and composite material in a flash flame environment when protected by a flame resistant (FR) fabric outer layer. This effort was conducted, funded, and managed by the US Army Natick Soldier Research, Development, and Engineering Center (NSRDEC) and was endorsed by Product Manager - Soldier Protective Equipment under a transition agreement in support of the Technology-Enhanced Capability Demonstration: Force Protection Soldier and Small Unit. UHMWPE material has excellent ballistic protection properties, but has generally not been considered for ballistic protection garments due to its low melting point. This research was conducted to determine if UHMWPE materials could be considered for use in the recently developed protective undergarment (PUG) if worn beneath an FR uniform.

Midscale and manikin flash flame tests were conducted at the NSRDEC Ouellette Thermal Test Facility (TTF). The manikin tests were conducted according to the ASTM F1930 Standard Test Method for Evaluation of Flame Resistant Clothing for Protection Against Fire Simulations Using an Instrumented Manikin. Special garments were constructed for testing on the thermal manikin. The UHMWPE materials were fabricated into undergarments consisting of shorts and a vest. An outer layer of FR material was fabricated into a coverall worn over the UHMWPE undergarments. The midscale flash flame tests were conducted with the same basic experimental setup as the ASTM F1930 test method, though they have not been adopted by ASTM. They were used for preliminary testing during design and fabrication of prototype garments with UHMWPE materials and FR fabrics. These tests helped guide the choice of materials and fabrics by showing the response of the material configurations as they were exposed to increasing durations of flash flame.

2 Background

2.1 UHMWPE Materials

UHMWPE fibers are manufactured from solvent based spinning processes and have very high tensile strength and stiffness (1). UHMWPE fibers also have low density and are flexible. These properties have made UHMWPE fibers beneficial in ballistic protection applications. The two most common trade names are Spectra from Honeywell (2) and Dyneema from DSM (3).

UHMWPE fibers have a low melting point at approximately 135 ⁰C to 150 ⁰C. A concern with any thermoplastic that has the potential for exposure to high heat or flame is the melting of the polymer into a liquid phase which could allow the hot material and flames to spread by dripping or flowing. In the case of thermoplastic materials in garments, there is concern that melted material may cause even more severe burn injuries by melting and re-solidifying over areas of burnt skin (4) (5).

2.2 Application: PUG

The motivation for this research project was related to the development of a PUG, which is worn beneath a protective outer garment (POG) to form a two-tier system designed to protect the pelvic region of dismounted soldiers. An example of a PUG prototype is shown in Figure 1.

Figure 1. Example of a PUG prototype (6)

The Army's current requirements for the PUG (7) include that no melt or drip occur when tested in accordance with ASTM D6413 Standard Test Method for Flame Resistance of Textiles (Vertical Flame Test) (8). Vertical flame tests are commonly used as the initial screening tool for determining the flammability or FR performance of a material. ASTM D6413 is conducted by suspending a fabric test specimen in a vertical position and exposing the edge to a controlled vertical flame for a 12-s exposure. Because of their low melting point, UHMWPE fabrics and composites fail the initial screening using ASTM D6413. They must be tested in combination with an outer FR shell material. ASTM F1358 Standard Test Method for Effects of Flame

Impingement on Materials Used in Protective Clothing Not Designated Primarily for Flame Resistance (9) is a vertical flame test that is used to assess a two-layer system. This test is conducted with an outer FR material folded around an inner non-FR layer of material.

2.3 Flash Flame Testing

The ASTM F1930 Test Method is used to evaluate FR clothing by predicting burn injury when exposed to a calibrated 84 kW/m^2 flash fire, generated with an array of propane burners (10). The test is conducted at the Ouellette TTF, as shown in Figure 2, with an instrumented manikin that measures heat flux through 123 insulated copper slug calorimeters. The Army specifies a 4-s flame duration for testing combat uniforms, and heat flux data are collected for a total of 120 s. The heat flux data are input into a skin burn injury model, which outputs a predicted burn injury level (severity and area).
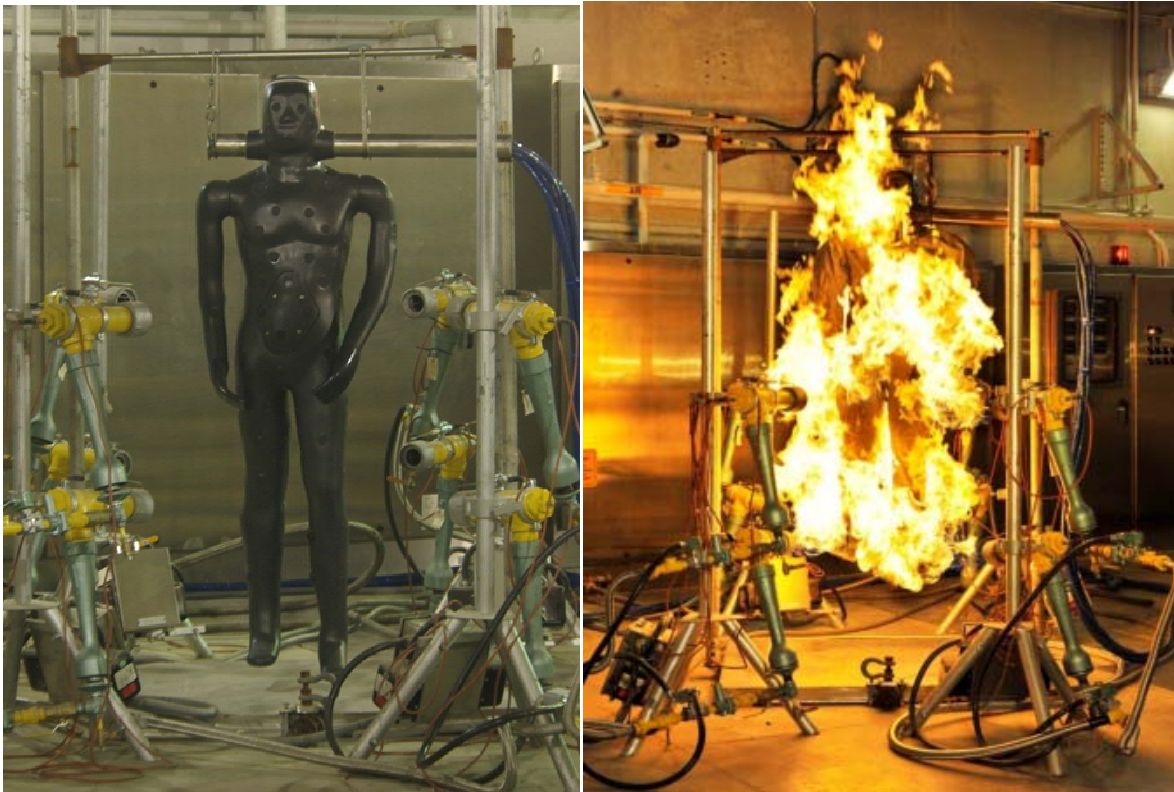
Figure 2. ASTM 1930 flash flame test conducted on thermal test manikin at Ouellette TTF

The physical response of the materials in the flash fire contains very important information to be gained from the test. An example of these observations could include self-extinguishing, continued burning, shrinkage, break-through, or melting and dripping of material. In many cases, the observed physical response of the materials during the test can be used to explain changes in the measured heat flux.

Compared to other methods of material testing, the flash flame test with an instrumented manikin has the advantage of taking into account the design features,

construction, and fit of a garment, as well as differences in protection based on how the garments are worn.

A cost-effective alternative to the manikin test for measuring and observing the response of a material against the flash flame is the midscale test. It includes the same basic experimental setup as the ASTM F1930 test, but in place of the instrumented manikin, material test specimens are mounted on a test panel or test cylinder. Since a smaller area is tested, the midscale test allows greater control of the standard target value of 84 kW/m^2 heat flux. With this increased control, the mid-scale test can be used to measure the response of a material or test a feature of a garment (i.e., seam, pocket, closure) without fabricating a full-scale test prototype.

3 Methodology

The UHMWPE materials were tested under an FR fabric. They were subjected to preliminary vertical flame tests in accordance with ASTM F1358 followed by midscale tests and manikin tests. The manikin tests were conducted in accordance with ASTM F1930. The midscale tests, which use the same basic experimental setup as the ASTM F1930 test, were performed with both a cylinder and a flat panel test apparatus. The FR fabric used as the outer layer was TenCate (improved) Defender M™ with the Operational Camouflage Pattern (OCP) print, which is the FR military fabric specified by the Army in the FR Army Combat Uniform (FRACU). The Defender M fabric weighs approximately 220 g/m^2 (6.5 oz/yd^2) and consists of 65% Lenzing FR rayon, 25% Twaron p-aramid, and 10% nylon (11).

Three different UHMWPE fabrics were used for testing: two plain woven and one knit. Both of the plain woven materials were sourced from Barrday Corp., one with 1200 denier (D) yarn and the other with 375D yarn. The knit material was manufactured for this project by Warwick Mills, with 650D UHMWPE yarn in a circular knit construction. An UHMWPE composite material for soft armor ballistic protection was also evaluated in the vertical flame and flat panel tests, but not in the cylindrical or manikin tests. This material is normally used in multi-layer configurations, but was tested as a single layer in this study for comparison with the woven and knit fabrics that were tested. All four materials are listed and described in Table 1.

Table 1. UHMWPE materials for testing.

Material	Construction	Thickness (mm)	Areal Density (g/m)^2
375D Yarn	Plain Weave	0.23	110
1200D Yarn	Plain Weave	0.51	228
650D Yarn	Knit	0.81	240
Composite*	0/90/0/90	0.25	180

*Tested only in vertical flame and flat panel testing

3.1 Vertical Flame Testing (ASTM F1358)

ASTM F1358, a vertical flame test method for a two-layer system, was conducted as a screening tool before flash flame testing. It specifies that ¾ inch of the folded material must protrude beyond the bottom edge of the specimen holding frame. To simplify the test setup for this project, this procedure was modified. The folded ends of the test specimens were aligned with the bottom of the frame, without any material protruding beyond the frame. In addition to these tests, one piece of UHMWPE 1200D fabric was tested without the outer layer of Defender M fabric, in accordance with ASTM D6413.

3.2 Flash Flame Testing

The midscale test is a more efficient means than the manikin test to develop an understanding between the relationship of heat input and material response. The

UHMWPE fabrics tested on the manikin were chosen based on results of several initial rounds of midscale testing. The midscale test is conducted with the same basic test setup as the ASTM F1930 instrumented manikin test, using a cylinder or flat panel test apparatus. All of the flash flame test apparatuses used (for both midscale tests and the manikin testing) were instrumented with copper slug calorimeters from Engineering Technology Incorporated (ETI). The calorimeter consisted of a 11.2-mm diameter, 1.3-g copper disk housed in an insulated holder. A thermocouple measured the temperature of the copper disk, and the heat flux was calculated from that temperature measurement. The measured temperature in the 13-sensor array on the flat panel midscale test during a 4-s calibration test is displayed in Figure 3.
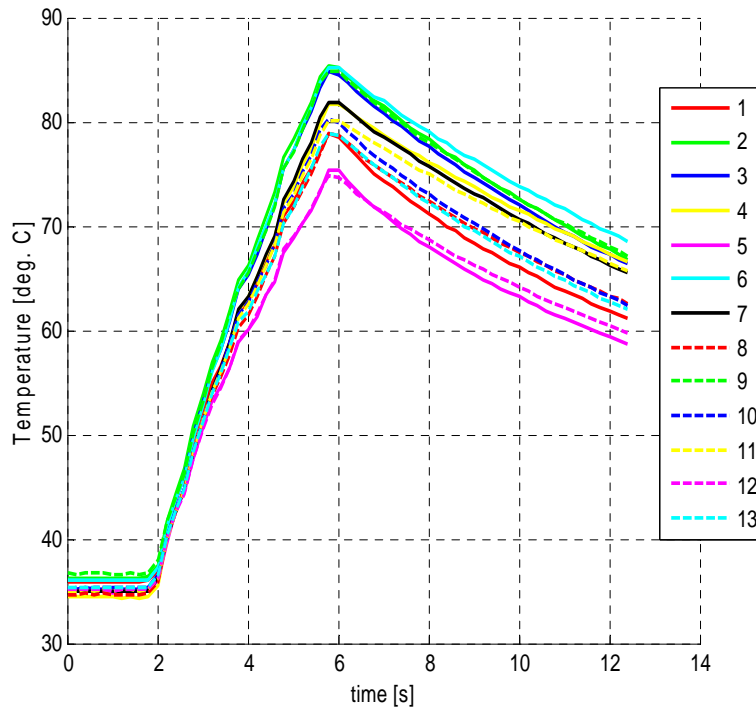
Figure 3. Temperature measurement of copper slug sensor for 4-s flame duration.

The method used to calculate the heat flux from the copper calorimeter temperature measurement, which is the standard practice at Ouellette TTF, was a variation of the method documented by the National Institute of Standards and Technology (NIST) (12). The NIST method uses temperature measurement (differential) to calculate the increase in thermal energy of the copper disk (Q_{Gain}) using the known mass (m) and specific heat (C_P) and change in temperature (ΔT):

$$Q_{Gain} = m\,C_p\,\Delta T \tag{1}$$

The rate of heat gain in the copper slug ($\dot{Q}_{Gain}$) is then divided by the known area of the copper disk (A) to obtain the heat gain per unit area.

$$\frac{\dot{Q}_{Gain}}{A} = \frac{m}{A}C_p\frac{dT}{dt} \tag{2}$$

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However, not all of the heat flux on the copper slug is captured directly by the temperature measurement, as some heat is lost from the copper slug to the environment through the insulated holder. This can be modeled with a heat loss per unit area ($\dot{q}_{Loss}$) proportional to the difference between the copper slug temperature and the initial temperature (T_o). The coefficient for this heat loss term (K) is determined empirically:

$$\dot{q}_{Loss} = K\left(T - T_o\right) \tag{3}$$

The heat balance of the sensor is used to calculate the heat flux on the outer surface of the sensor ($\dot{q}_{Surface\ Flux}$) by solving for this value:

$$\dot{q}_{Surface\ Flux} = \frac{\dot{Q}_{Gain}}{A} + \dot{q}_{Loss} \tag{4}$$

The variation in the NIST analysis used at TTF is to allow T_o in the loss term to vary with time. T_o varies according to an empirically based lumped parameter model of the material surrounding the copper slug. This variation is required to remove extended duration offsets in the calculated heat flux, which are caused by the loss term. The heat flux on the copper slug sensor, calculated with this variation of the NIST method from the temperature profiles in Figure 3, is shown in Figure 4. All the heat flux data presented in Chapter 4 of this report was filtered with a 2-point running average.
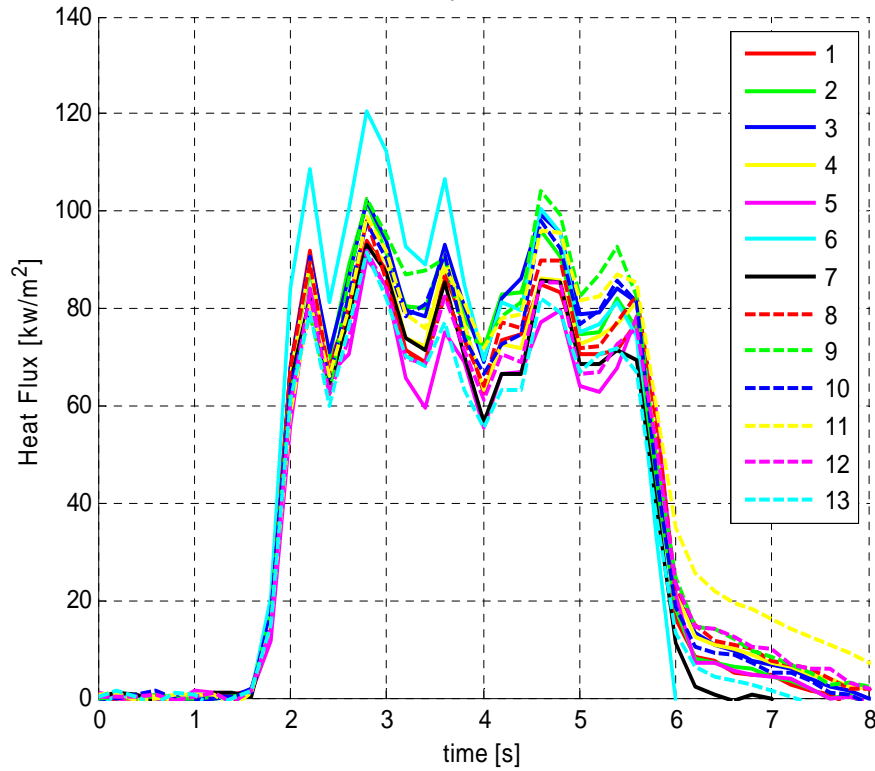
Figure 4. Heat flux calculated from copper slug temperature measurement for 4-s flame duration.

3.2.1 Midscale Tests

As previously mentioned, both cylindrical and flat plate midscale tests were conducted. A diagram of the midscale test setup (with the cylinder) is shown in Figure 5.
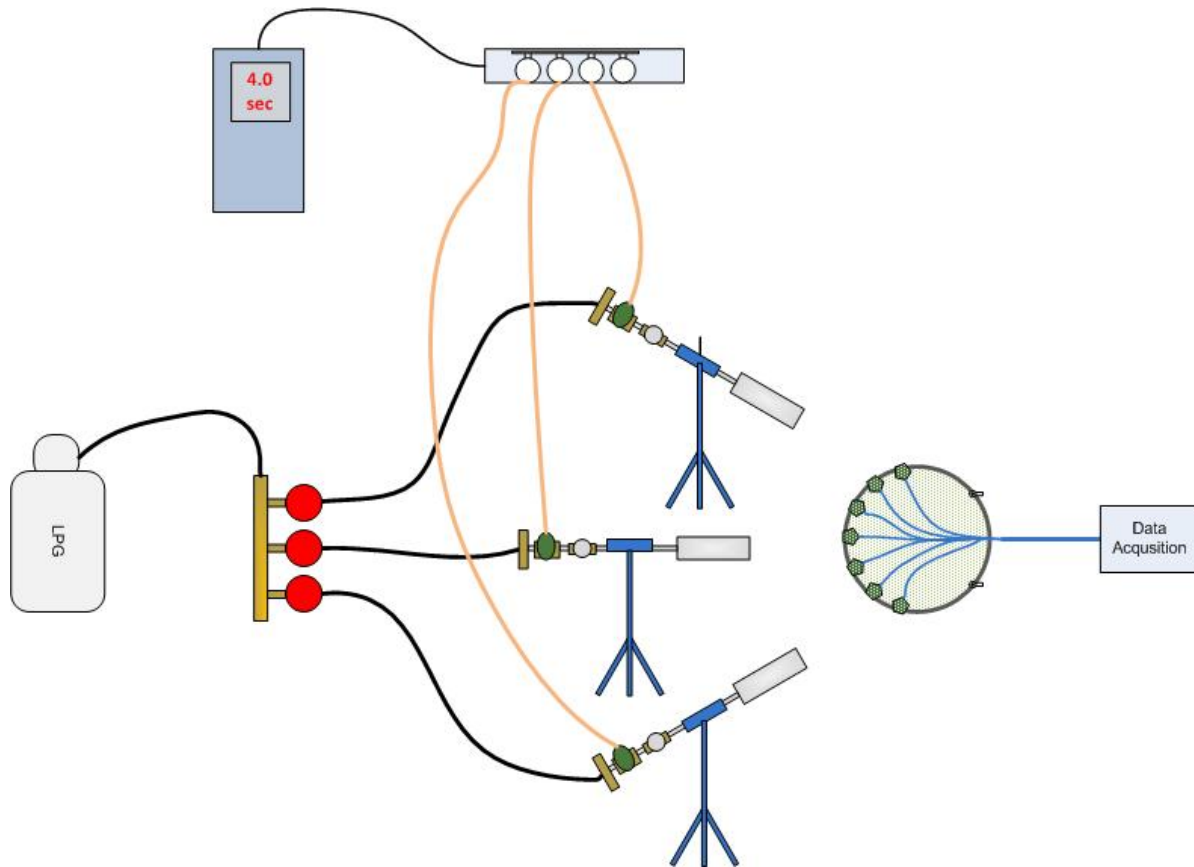
Figure 5. Midscale test setup.

The flash fire for both midscale test apparatuses was controlled by simultaneously opening a solenoid valve for each burner. The duration of the opening was set with an electronic timer. The data acquisition system recorded data from each of the heat flux sensors at a sampling rate of 5 Hz.

The heat flux on the midscale test apparatus (cylinder or flat plate) was calibrated to within +/- 5% of the target 84 kw/m^2 by adjusting the standoff and positioning of the burner flame. Propane is supplied to the burners at 25 psi, and for these tests, a 3/16-inch burner orifice was used.

3.2.1.1 Cylindrical Test

The cylindrical midscale test requires approximately 2/3 yd of material (24 in by 50 in) wrapped around the 13.5-inch diameter test cylinder as shown in Figure 6a, and clamped on the back side of the cylinder as shown in Figure 6b. The circumference of the test cylinder is 42-inches, which is equal to the chest circumference of the thermal test manikin. The cylinder is constructed of Norplex-Micarta NP300 Series phenolic-cotton composite. The uncovered test cylinder is shown in Figure 6c.
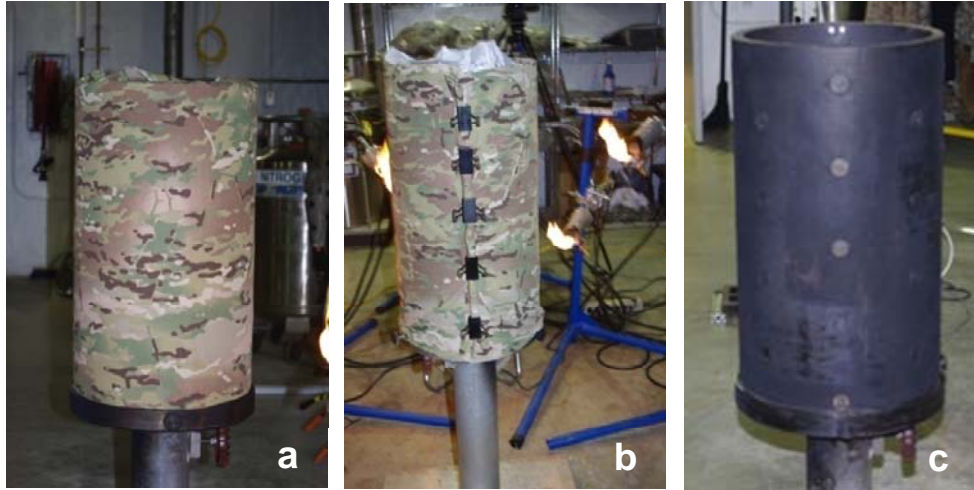
Figure 6. Cylindrical midscale test apparatus: a) Material wrapped around test cylinder; b) Material clamped on back of test cylinder; c) Bare test cylinder.

There were 23 heat flux sensors arranged on 180° of the front side of the test cylinder. The sensors are arranged in offset rows (three rows of five sensors and two rows of four sensors) with 5 inches of spacing between each sensor. The front view of the test cylinder is shown in Figure 7.
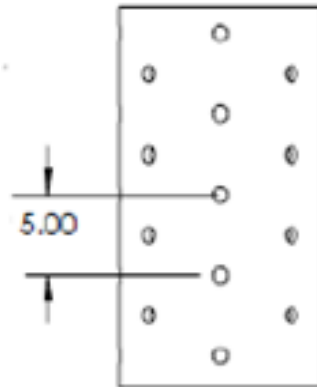
Figure 7. Front view of test cylinder showing 13 of 23 sensor positions.

3.2.1.2 Flat Panel Test

The flat panel midscale test requires a 20-inch square sheet of material, which in this study was clamped around the 13-inch square test panel as shown in Figure 8a. Preliminary tests using three different clamping configurations (described and shown in Appendix A) were performed to determine the best configuration. The flat panel test apparatus used in this testing had an array of 13 heat flux sensors arranged around the center of the panel as shown in Figure 8b.
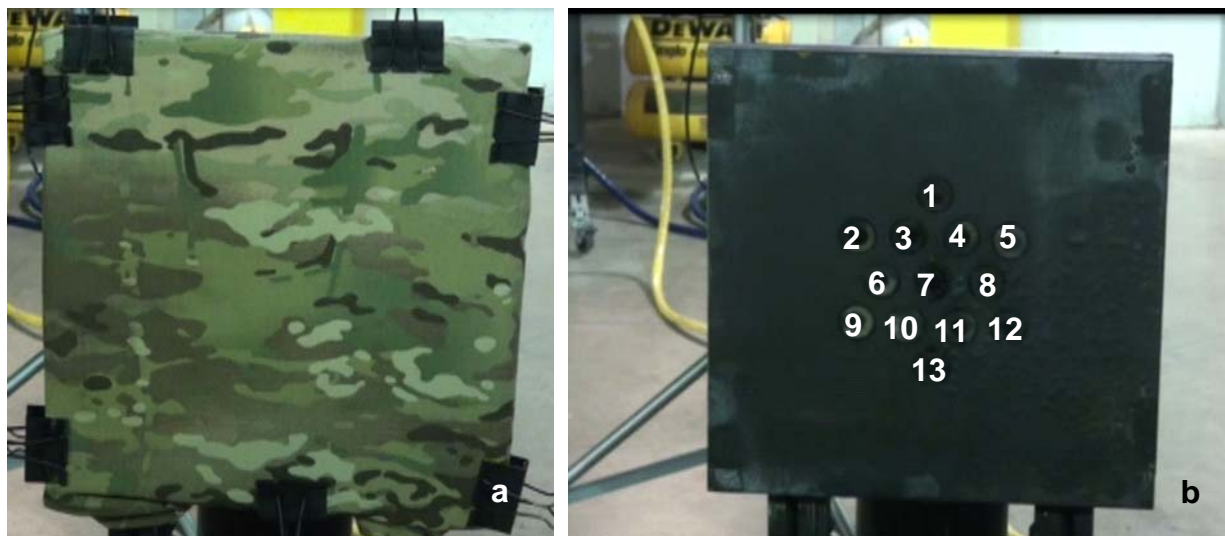
Figure 8. Flat panel midscale test apparatus: a) Material clamped around square test panel; b) Bare square test panel with numbered sensors.

3.2.2 Manikin Test

Special garments were designed and fabricated by the NSRDEC Design and Pattern Prototype Shop for testing according to ASTM F1930 on the thermal test manikin. These garments were designed to test the UHMWPE materials when shielded by one layer of the Defender M fabric. The UHMWPE materials were fabricated into simple undergarments consisting of a vest and pair of boxer shorts, as shown in Figure 9a. The Defender M fabric was fabricated into a single layer coverall, which was worn over the UHMWPE undergarments on the test manikin, shown in Figure 9b.

The undergarments and coverall combination provided a two-layer material configuration over the shorts and vest area of the test manikin, with only one layer of FR material shielding the UHMWPE fabrics. The FRACU consisted of a shirt tucked into a pair of pants, as well as many pockets and other design features, so there would be more than one layer of FR fabric over much of the manikin surface area. The coverall and undergarment tests were designed so the UHMWPE materials would not be provided additional protection due to the design features in a uniform. One set of UHMWPE undergarments was tested underneath the FRACU shirt and pants for a comparison with the results of the coveralls. The FRACU fabric was printed with the Universal Camouflage Pattern (UCP).

The Defender M garments were laundered in accordance with ASTM F1930. The UHMWPE undergarments were not laundered. Each specimen was conditioned for at least 24 h at 70 ±5 °F (20 ± 2 °C) and 65 ± 5-% relative humidity and tested within 30 min of removal from the conditioning area as specified in the test method.

Figure 9. Test garments on thermal test manikin: a) Vest and boxer shorts; b) Defender M coverall.

When comparing the heat flux data from different materials, the analysis team took the differences in the area covered by the UHMWPE undergarments and the cotton undergarments into account. The cotton undergarments included of a pair of briefs, instead of shorts, so there was no coverage of the upper thighs. For comparison between materials, the "briefs area" is used to refer to the sensors that were covered by the cotton briefs and the UHMPWE shorts, ignoring the sensors on the upper thigh (which were covered only by the shorts). The cotton T-shirt also hung below the waist and covered the entire area of the briefs. Therefore, the briefs area in the cotton undergarment tests was covered by two layers (the briefs and the overhanging T-shirt). There was a difference in area coverage between the cotton T-shirt and UHMWPE vest. Two sensors on the shoulders were covered by the T-shirt sleeves, but were not covered by the vest. These sensors were ignored by comparing sensors only in the "vest area" on the torso. The sensors covered by the briefs area and the vest area are shown in Figure 10.
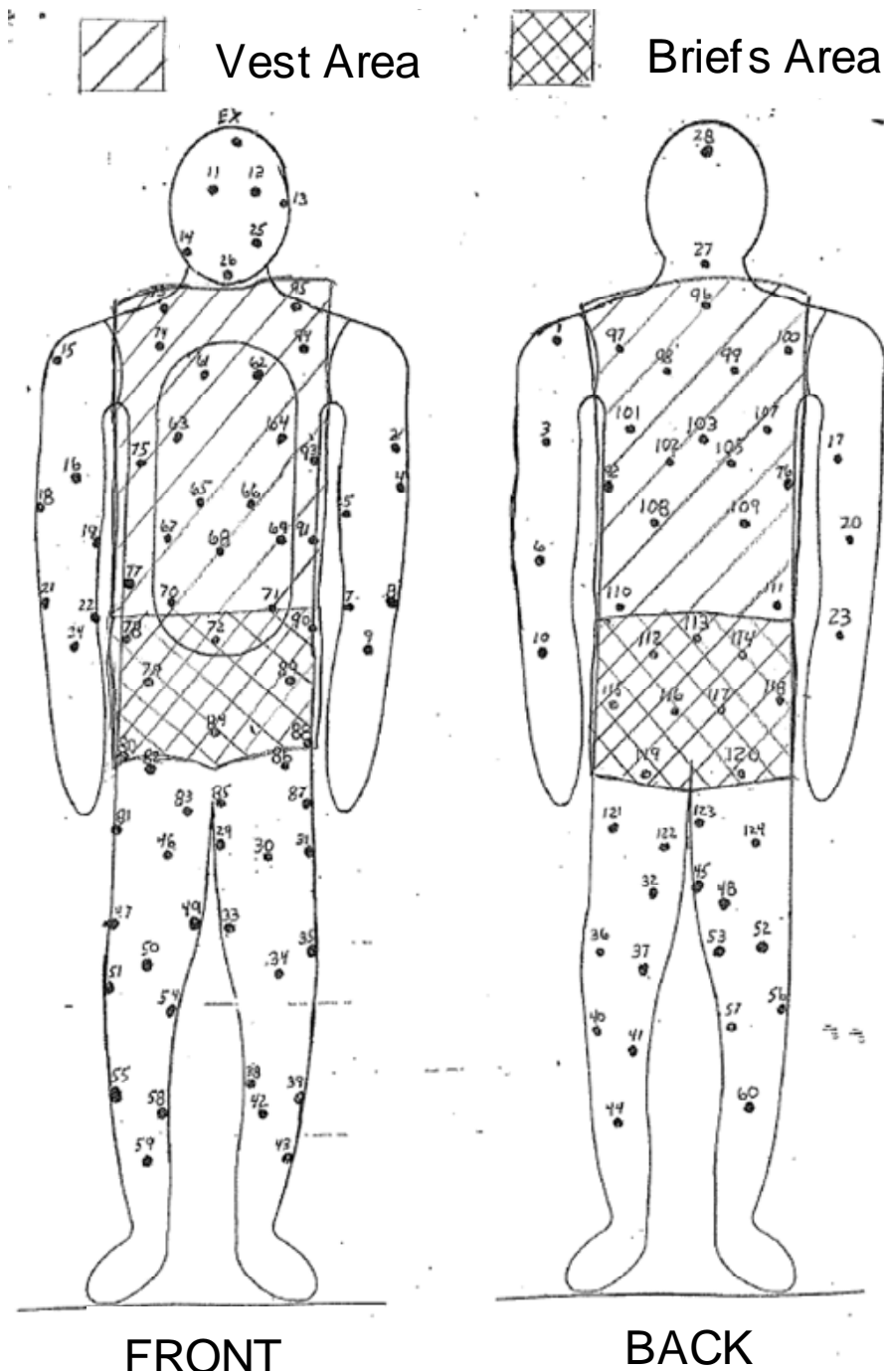
Figure 10. Manikin sensor areas for comparison of materials.

Five UHMWPE undergarment sets were tested underneath the Defender M coveralls, and one UHMWPE undergarment set was tested underneath a FRACU. Two sets of coveralls were tested with cotton undergarments, and one set of coveralls was tested with no undergarments to provide a control for the UHMWPE tests. Additionally, a FRACU was tested with cotton undergarments. The composite material was not tested on the manikin, as it is not a suitable material for fabrication of the vest and shorts prototypes.

The test matrix was completed on two separate days, as shown in Table 2. All of these tests were conducted with a 4-s flash flame duration calibrated to +/- 5% of 84 kW/m^2, according the ASTM F1930.

Table 2. Thermal manikin test matrix.

		FR Outer Layer	Undergarments
Day 1	Test 1	Defender M Coveralls	None
	Test 2	Defender M Coveralls	UHMWPE 375D Woven
	Test 3	Defender M Coveralls	UHMWPE 1200D Woven
	Test 4	Defender M Coveralls	UHMWPE - 375D Woven
	Test 5	Defender M Coveralls	Cotton T-Shirt & Briefs
Day 2	Test 1	Defender M Coveralls	Cotton T-Shirt & Briefs
	Test 2	FRACU Shirt and Pants	Cotton T-Shirt & Briefs
	Test 3	FRACU Shirt and Pants	UHMWPE 375D Woven
	Test 4	Defender M Coveralls	UHMWPE 650D Knit
	Test 5	Defender M Coveralls	UHMWPE - 375D Woven

4 Results and Discussion

4.1 Vertical Flame Test (ASTM F1358) Results

ASTM F1358 vertical flame tests were conducted on the combinations of UHMWPE materials and Defender M fabric. As described in Section 3.1, a minor variation of the ASTM F1358 was used for the test. The test results, showing after-flame and after-glow durations and the burn length, are displayed in Table 3.

Table 3. Vertical flame test results.

Inside Layer	After-Flame (s)	After-Glow (s)	Burn Length (inches)	
			Outside	Inside
1200D UHMWPE Plain Weave	0	0	3.25	1.00
375D UHMWPE Plain Weave	0	0	2.63	0.75
650D UHMWPE Knit	0	0	2.25	1.50
UHMWPE Soft Armor Composite	0	3.6	2.75	2.75

All of the test specimens self-extinguished after the 12-s exposure to the vertical flame, with no after-flame. The exterior condition of the folded-over test specimens is shown in Figure 11. Each specimen shows a similar char length at the folded edge of the material, which was exposed to the flame.
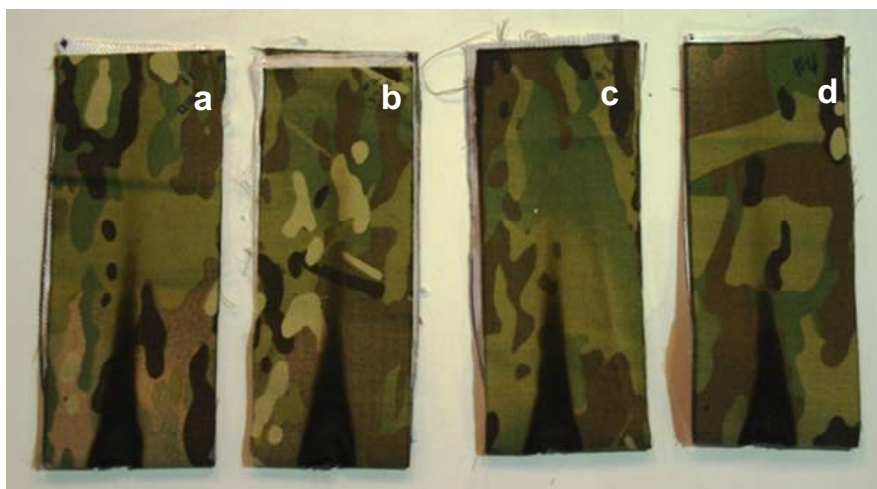
Figure 11. Exterior condition of combined Defender M and UHMWPE material specimens after vertical flame test: a) UHMWPE 1200D plain weave; b) UHMWPE 375D plain weave; c) UHMWPE 650D knit; d) UHMWPE soft armor composite.

The interior condition of the test specimens, showing the UHMWPE materials, is shown in Figure 12. There was no dripping of melted material from any of these test specimens.
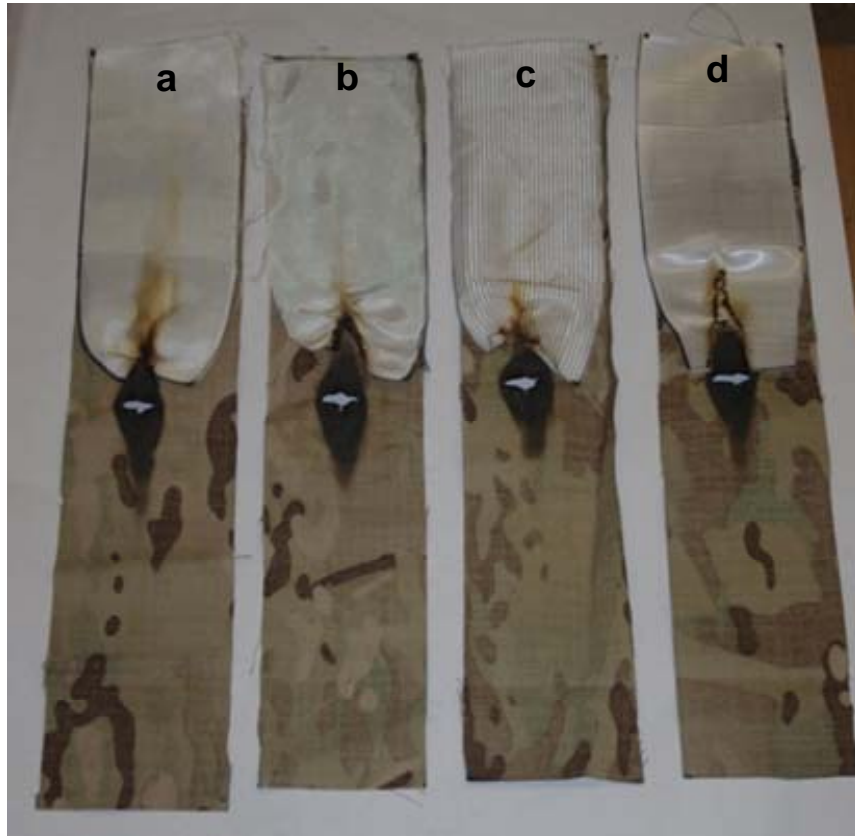
Figure 12. Interior condition of combined Defender M and UHMWPE material specimens after vertical flame test: a) UHMWPE 1200D plain weave; b) UHMWPE 375D plain weave; c) UHMWPE 650D knit; d) UHMWPE soft armor composite.

One test specimen of UHMWPE 1200D fabric was tested by itself (i.e., without the outer layer Defender M, in accordance with ASTM D6413). It continued to burn for over 2 min after removal of the flame, until most of the material was consumed or fell to the bottom of the test chamber and cooled. This was expected, as the UHMWPE materials are not FR and have a low melting temperature.

4.2 Midscale Test Results

The tests conducted with the cylindrical midscale and flat panel midscale differ in that the flat panel allows the material to be clamped around each edge of the flat panel, while in the tests conducted on the cylinder, the material was not clamped on the top and bottom edges. Because the material on the cylindrical midscale test was not clamped or secured around the top and bottom circumference of the cylinder, it appeared that the flames and/or hot gasses may have been propagating behind the FR outer layer, allowing flames and convective heat flow directly to the UHMWPE materials. As can be seen in Section 4.2.1, this effect resulted in increased damage to both the UHMWPE fabric under layer and Defender M outer layer. As can be seen in Section 4.2.2, this effect was prevented in the flat panel midscale test setup by clamping the fabric on all four sides as shown in Figure 8a.

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4.2.1 Cylindrical Test Results

The first round of flash flame testing was conducted with the cylindrical midscale test. Results are shown from testing the UHMWPE 1200D with Defender M and with 50% nylon/50% cotton (NyCo) shielding fabrics and the 375D with Defender M. The observed response of the 650D knit and Defender M was very similar to the 1200D and is not shown in this report. The results of one test with the UHMWPE 1200D fabric and no FR shielding fabric is shown, to demonstrate the response when the UHMWPE is exposed to direct flame contact. The UHMWPE composite was not tested due to the difficulty in mounting this material on the cylinder.

4.2.1.1 Cylindrical Test of UHMWPE 1200D Plain Weave Fabric Under Defender M

The first material tested was the UHMWPE 1200D Plain Weave, which was layered underneath the Defender M fabric. The material was tested with a 4-s flash flame at the calibrated 84 kW/m^2 heat flux. The condition of the Defender M before and after the test and the condition of the UHMWPE fabric after the test are shown in Figure 13.

The Defender M outer layer continued to burn after the 4-s flash flame duration and self-extinguished after 2-3 s. The Defender M remained charred after the test, as shown in Figure 13b. The condition of the UHMWPE 1200D woven fabric, in Figure 13c, showed very little damage, with only some areas of minor distortion.
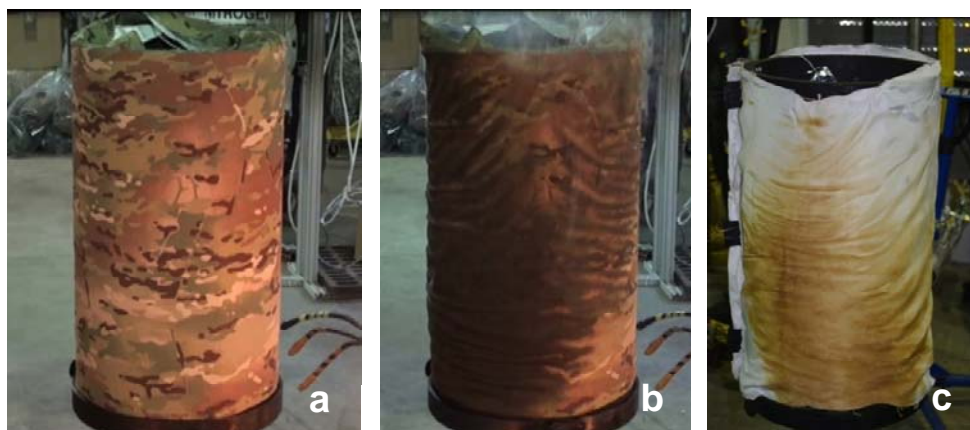
Figure 13. Cylindrical midscale test of Defender M and UHMWPE 1200D plain weave: a) Defender M before test; b) Defender M after test; c) UHMWPE fabric after test.

The yellow residue visible on the UHMWPE woven fabric in Figure 13c is assumed to be a product of incomplete combustion of the Defender M. This yellow residue was visible on all the materials tested under the Defender M fabric when it became charred during the test. The yellow residue was also visible on a cotton T-shirt after it was tested on the midscale cylinder underneath the Defender M layer. Future testing will be conducted to characterize this residue and to determine how it was formed during the decomposition and combustion of the fabric.

4.2.1.2 Cylindrical Test of UHMWPE 1200D Plain Weave Fabric Without FR Shielding

In order to show the importance of using an FR material to shield the UHMWPE layer, the same 4-s flash flame test was conducted with a NyCo fabric shielding the UHMWPE 1200D undergarment. The condition of the fabric after the test is shown in Figure 14.
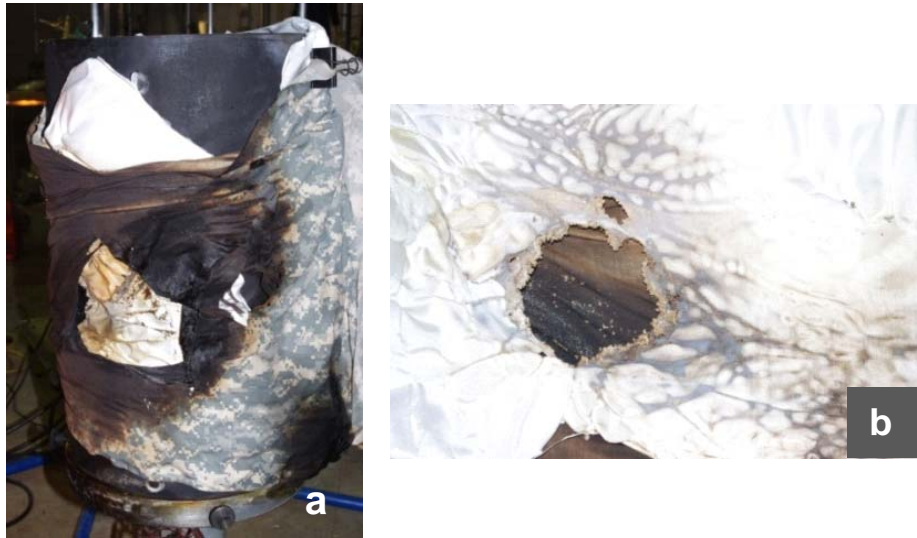
**Figure 14. Cylindrical midscale test of NyCo and UHMWPE 1200D plain weave:
a.) Both materials after test; b.) Close up of UHMWPE fabric after test.**

The fabric continued to burn and did not self-extinguish after the 4-s flash flame test. It was manually extinguished with a water spray. The NyCo material did not remain intact, and a hole burned through the fabric as shown in Figure 14a. This allowed direct flame exposure on the UHMWPE material, which melted and burned as shown in Figure 14b.

To show the results of direct flash flame exposure on the UHMWPE materials, one test was conducted with the UHMWPE 1200D plain weave material with no outer layer for protection. The UHMWPE fabric immediately began disintegrating during the flash flame exposure. During the test, one end of the UHMWPE fabric immediately broke away from the clamps that were holding it in place on the cylinder. Very little material was remaining on the test cylinder after the test. The results immediately after the 4-s flame exposure are shown in Figure 15a, where some flaming material can be seen falling from the test cylinder.

The material in this test displayed a response that was different than normal melt/drip behavior. Figure 15b shows a close up view of the UHMWPE material after the test. There were places where the fabric material appeared to have melted and re-solidified, creating areas of solid plastic, instead of the original woven fabric structure. The areas where the UHMWPE material melted and burned away are visible in the shredded appearance at the edge of the fabric in Figure 15b.
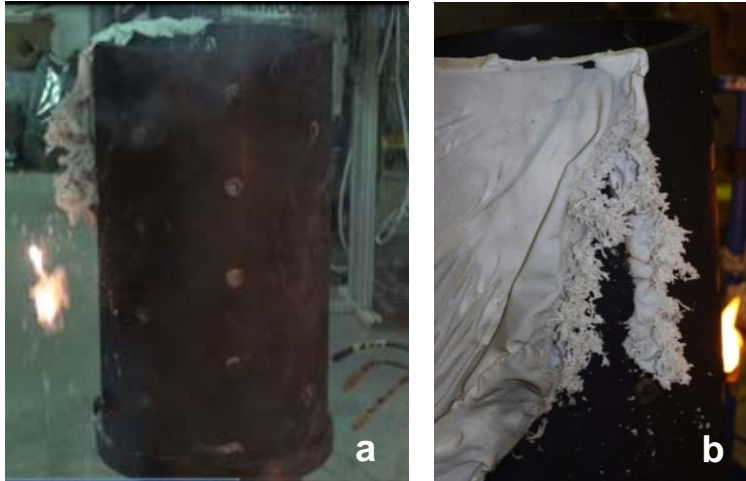
Figure 15. Cylindrical midscale test of UHMWPE 1200D plain weave fabric with direct flame exposure immediately after test: a) Cylinder; b) Close up view of UHMWPE material.

4.2.1.3 Cylindrical Test of UHMWPE 375D Plain Weave Fabric Under Defender M

The UHMWPE 375D woven material had an areal density of approximately one-half of the 1200D woven or 650D knit materials. After the 4-s flash flame test, the UHMWPE 375D plain weave showed significant shrinkage and melting behind the outer Defender M layer, as shown in Figure 16a. Most of this damage occurred from the edges of the material, especially from the bottom edge of the woven UHMWPE fabric, as shown in Figure 16b.
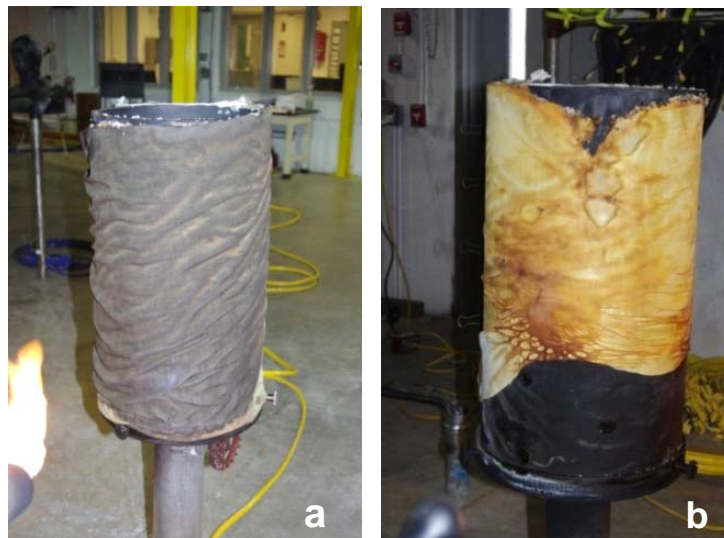
Figure 16. Cylindrical midscale test of Defender M and UHMWPE 375D plain weave after test: a) Outer layer; b) Under layer.

4.2.2 Flat Panel Test Results

4.2.2.1 Flat Panel Test of Defender M Fabric

The increased control of the flat panel midscale test allowed measurements and observations of a transition in the Defender M fabric after approximately 4 to 5 s in the 84 kW/m^2 flame exposure. The transmitted heat flux through the Defender M fabric increased rapidly during this interval, as displayed in Figure 17. The condition of the fabric test specimens after each of these exposures is shown in Figure 18.
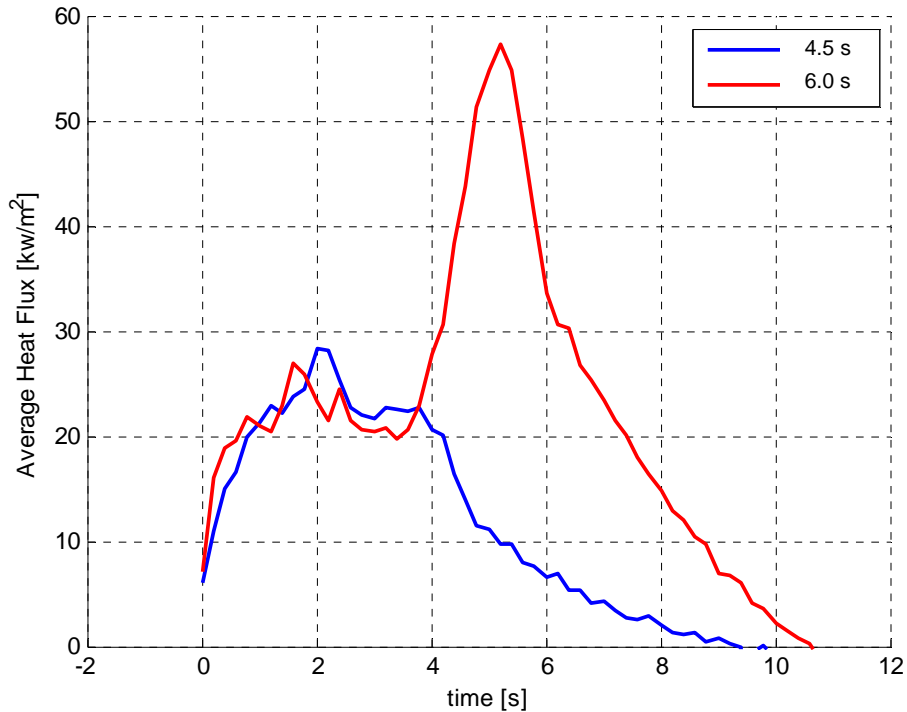
Figure 17. Flat panel midscale test of heat flux transmitted through Defender M fabric – 4.5-s and 6-s flame durations.
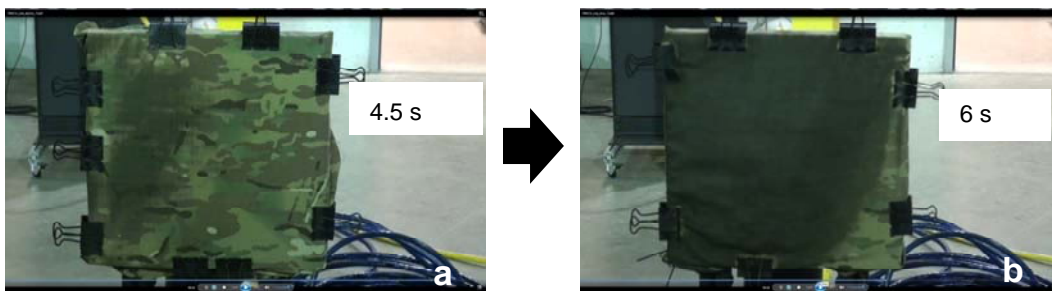
Figure 18 Flat panel midscale test of Defender M fabric: a) After 4.5 s; b) After 6 s.

This behavior exhibited by the Defender M fabric is important to consider when analyzing the test data of the UHMWPE materials tested behind the Defender M outer layer. None of the UHMWPE fabric materials tested on the flat panel behind the Defender M showed any visible damage after the 4-s flash flame duration at 84 kW/m^2. For this reason, the combinations of UHMWPE fabric under the Defender M fabric were

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tested with flame durations longer than 4 s in order to observe any significant response of the materials.

4.2.2.2 Flat Panel Test of UHMWPE 375D Plain Weave Fabric Under Defender M

The UHMWPE 375D plain weave fabric was the lightest weight UHMWPE fabric of those tested in this study (110 g/m^2). The lighter weight fabric and lower denier yarns have less capacity to absorb thermal energy before they melt and degrade. The condition of the Defender M outer layer and UHMWPE 375D under layer after a series of tests at increasing flame durations with the flat panel midscale test is displayed in Figure 19. Each column of photos shown was an individual test conducted with different test specimens.

Defender M (FR) Outer Layer

375D UHMWPE Plain Weave (tested under Defender M)

4 s   4.5 s   5 s   6 s

Figure 19. Flat panel midscale test of Defender M outer layer and UHMWPE 375D plain weave under layer with increasing flash flame duration.

The rapid transition of the Defender M fabric was observed between the 4-s and 5-s tests. Up until 4 s, the FR protection of the Defender M prevented any visible damage to the UHMWPE 375D woven under layer. The condition of the material after the 5-s test was drastically different, as the Defender M had a black charred appearance, and the UHMWPE layer had melted and burned away from nearly half of the flat panel. The test conducted with 6 s of flame duration showed additional melting and burning of the fabric off the flat panel. The transmitted heat flux measured on the flat panel for each of these tests is displayed in Figure 20.

Figure 20. Flat panel midscale test heat flux transmitted through Defender M outer layer and UHMWPE 375D plain weave under layer with increasing flash flame duration.

Each transmitted heat flux trace plotted in Figure 20 is the average of the 13 heat flux sensors on the flat panel. Each test of incremental flame duration shows an increase in the transmitted heat flux. The 4-s and 4.5-s tests showed similar heat flux levels, with an increase in duration and total heat for the 4.5-s test. As the heat flux shielding provided by the Defender M was reduced after 4.5 s, the UHMWPE fabric was exposed to a higher heat flux. This increased heat flux was sufficient to cause rapid damage to the UHMWPE 375D woven under layer. When the under layer melted and burned away to uncover the heat flux sensors, there was a greater increase in heat flux transmission as they were only shielded by the charred Defender M fabric.

4.2.2.3 Flat Panel Test of UHMWPE 1200D Plain Weave Fabric Under Defender M

As previously mentioned, the UHMWPE 1200D plain weave fabric was more than twice as heavy as the 375D plain weave. When tested behind the Defender M, this heavier UHMWPE fabric remained intact with flame durations up to 8 s. There were no holes burnt through the fabric in this series of tests, as shown in Figure 21. A significant amount of fabric distortion was visible in the lower left hand corner of the 1200D woven under layer after the 8-s test.

Defender M (FR) Outer Layer

| | 5 s test | 6 s test | 7 s test | 8 s test |

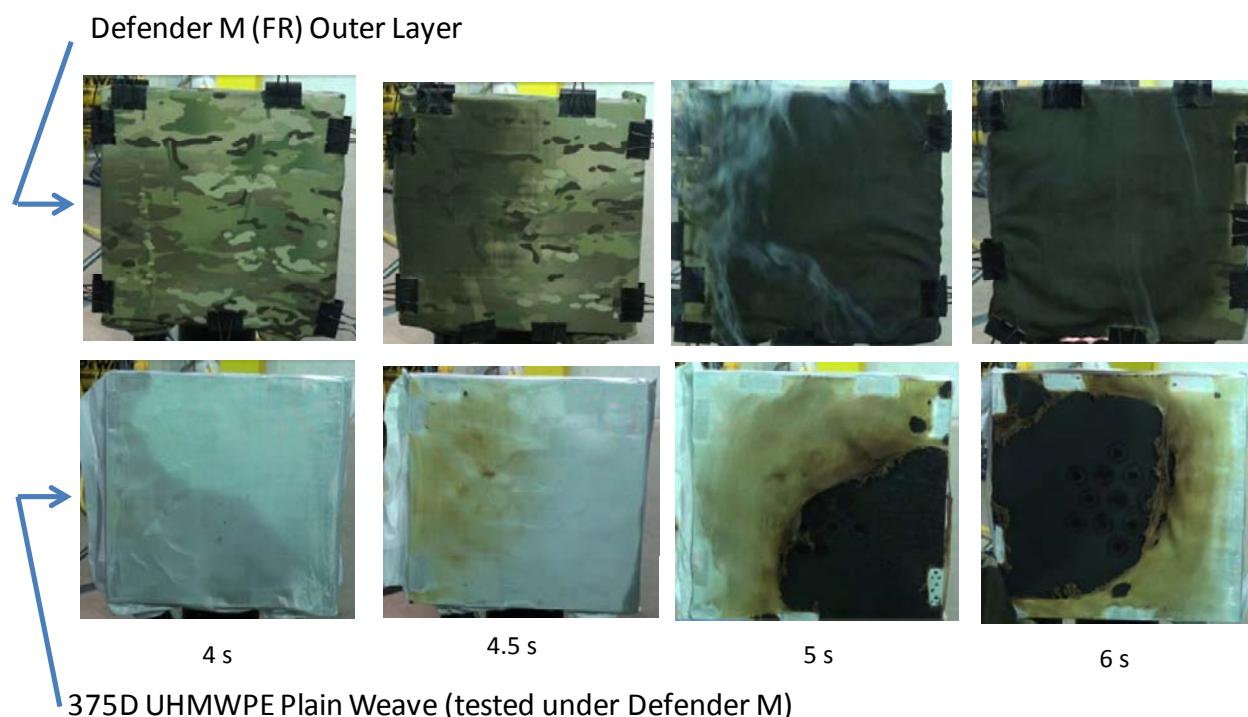1200D UHMWPE Plain Weave (tested under Defender M)

Figure 21. Flat panel midscale test of Defender M outer layer and UHMWPE 1200D plain weave under layer with increasing flash flame duration.

The transmitted heat flux through the fabric layers on the flat test panel is plotted in Figure 22 for this series of tests.
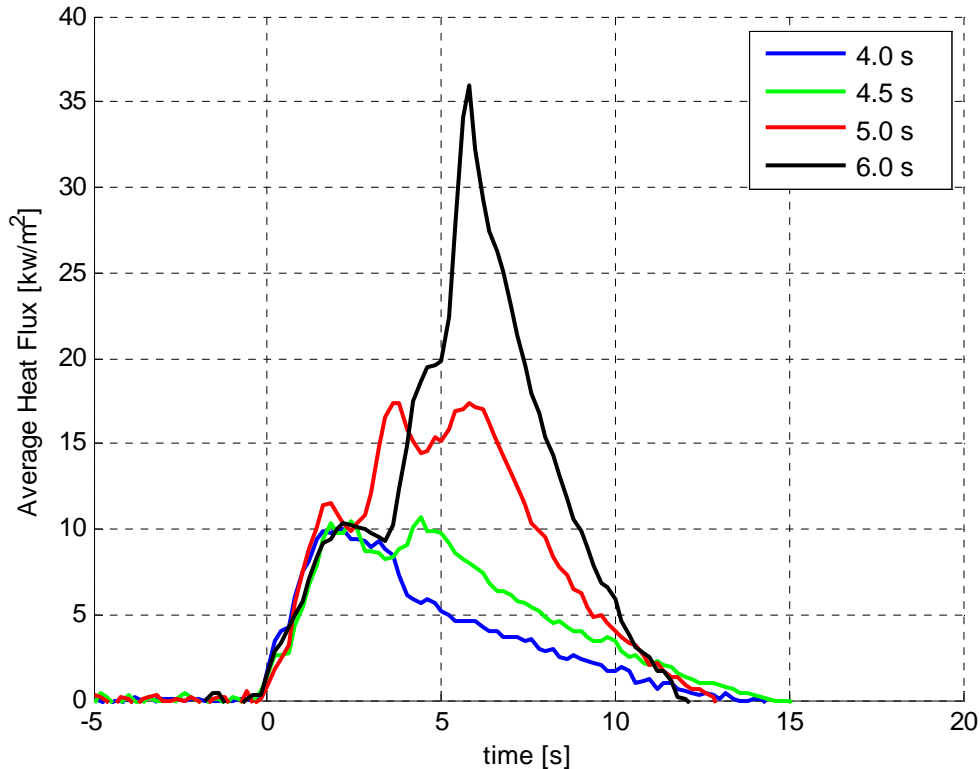

Figure 22. Flat-panel midscale test heat flux transmitted through Defender M outer layer and UHMWPE 1200D plain weave under layer with increasing flash flame duration.

There was an increase in the transmitted heat flux after 4 s, which corresponds with the behavior of the Defender M in the flash fire test. After this point the UHMWPE 1200D

under layer was continuing to reduce the transmitted heat flux, as it absorbed thermal energy while increasing in temperature. In all cases, if the UHMWPE material under layer remained intact, it reduced the transmitted heat flux to the panel sensors.

4.2.2.4 Flat Panel Test of UHMWPE 650D Knit Fabric Under Defender M

Although the UHMWPE 650D knit fabric had a similar areal density to the 1200D, it was approximately 60% thicker with a more open and permeable fabric construction. Figure 23 shows the condition of this fabric behind the Defender M outer layer for flash flame durations up to 8 s.

Defender M (FR) Outer Layer

4.25 s test   6 s test   8 s test
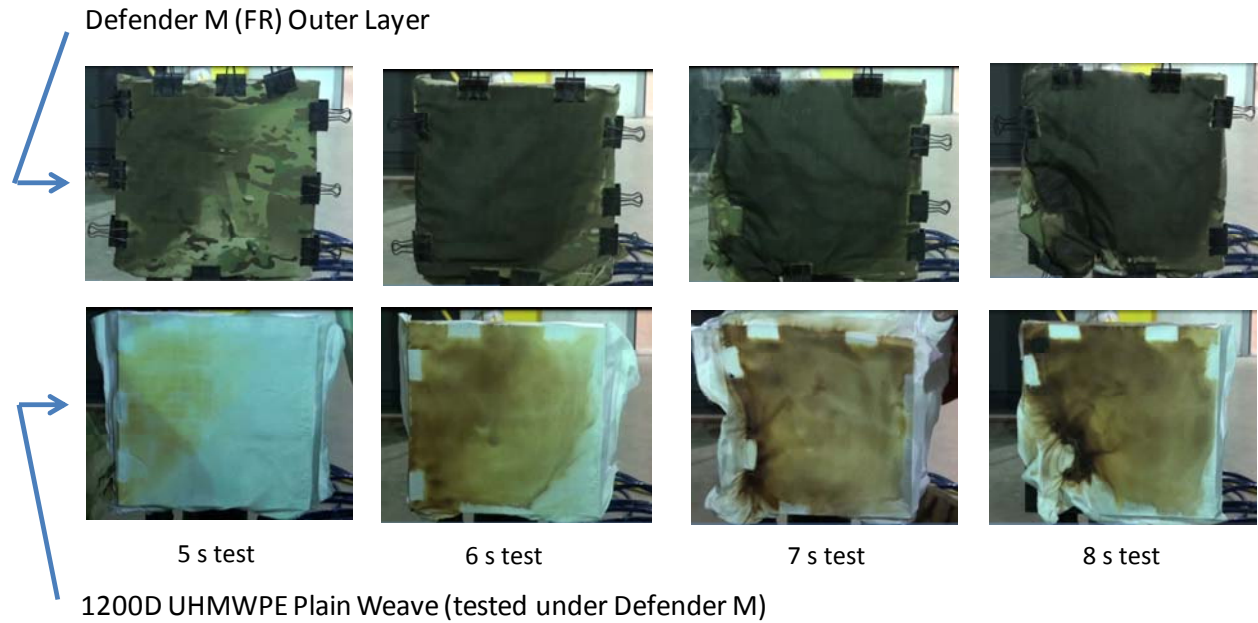
650D UHMWPE Knit (tested under Defender M)

Figure 23. Flat panel midscale test of Defender M outer layer and UHMWPE 650D knit under layer with increasing amounts of flash flame duration.

As with the other UHMWPE fabric materials, there was almost no damage to the fabric observed at a flame duration of approximately 4 s. Some distortion of the fabric was observed after the 6-s test. The inspection of the fabric after the 8-s test showed that two large holes had opened up. Some of the material had melted and burned away from the test panel, and some had recoiled and rolled up around the edges of the holes. The more open knit construction of this fabric resulted in more damage to the material during the 8-s flame test than to the1200D plain weave. The transmitted heat flux for the 650D knit fabric tests behind the Defender M outer layer are displayed in Figure 24.

The heat flux transmitted through the 650D knit material was higher than the 1200D woven material because of the open knit fabric structure.

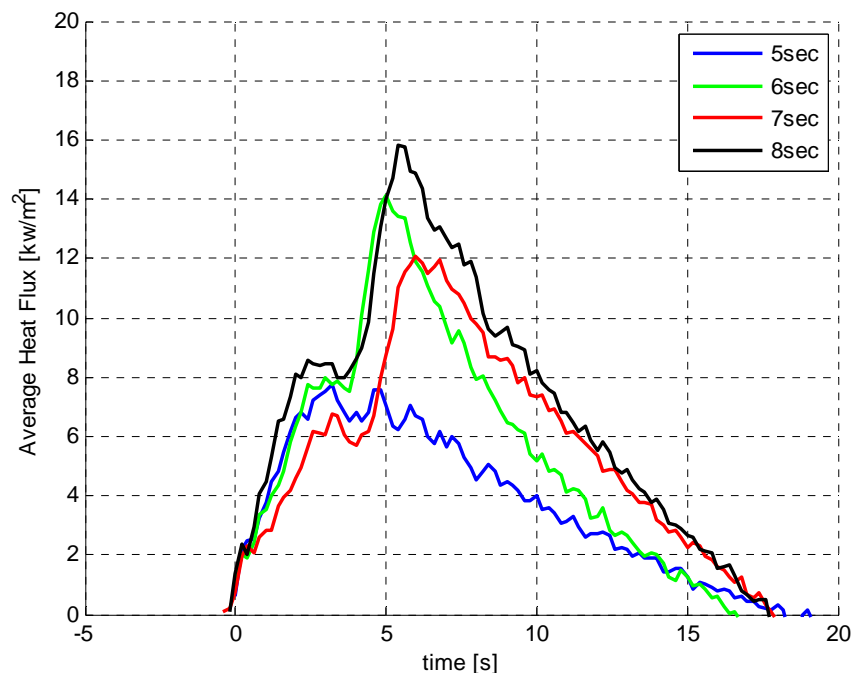**Figure 24. Flat panel midscale test heat flux transmitted through Defender M outer layer and UHMWPE 650D knit under layer with increasing amounts of flash flame duration.**

4.2.2.5 Flat Panel Test of UHMWPE Soft Armor Composite (One Layer) Under Defender M

One layer of the UHMWPE soft armor composite consisted of four plies of fiber oriented in a 0/90/0/90 configuration. While the other materials that were tested consisted of different fabric constructions of only UHMWPE fiber, the composite included a resin which binds together the unidirectional fibers in each ply, as well as binding the four plies into one sheet.

Because it was less flexible than the fabric materials, the composite test specimen was cut to exactly the size of the 13-inch x 13-inch test panel, and was secured to the panel around the edges with high temperature tape. A 20-inch x 20-inch sheet of Defender M was then placed over the test specimen and folded around the panel. This was a different method than was used to mount the other UHMWPE fabric test specimens, which were cut to 20 inches x 20 inches and folded around the test panel with the Defender M fabric. The composite will therefore have edges located on the test panel, which could be more susceptible to thermal damage than the fabric materials, which were folded around the panel.

The results of testing one layer of the UHMWPE composite material, behind the Defender M fabric, at flash flame durations up to 8 s, are shown in Figure 25. (Note: Product numbers on the test specimens have been blocked out).

Defender M (FR) Outer Layer

| 4 s test | 5 s test | 6 s test | 8 s test |

UHMWPE Soft Armor Composite (1 layer, tested under Defender M)
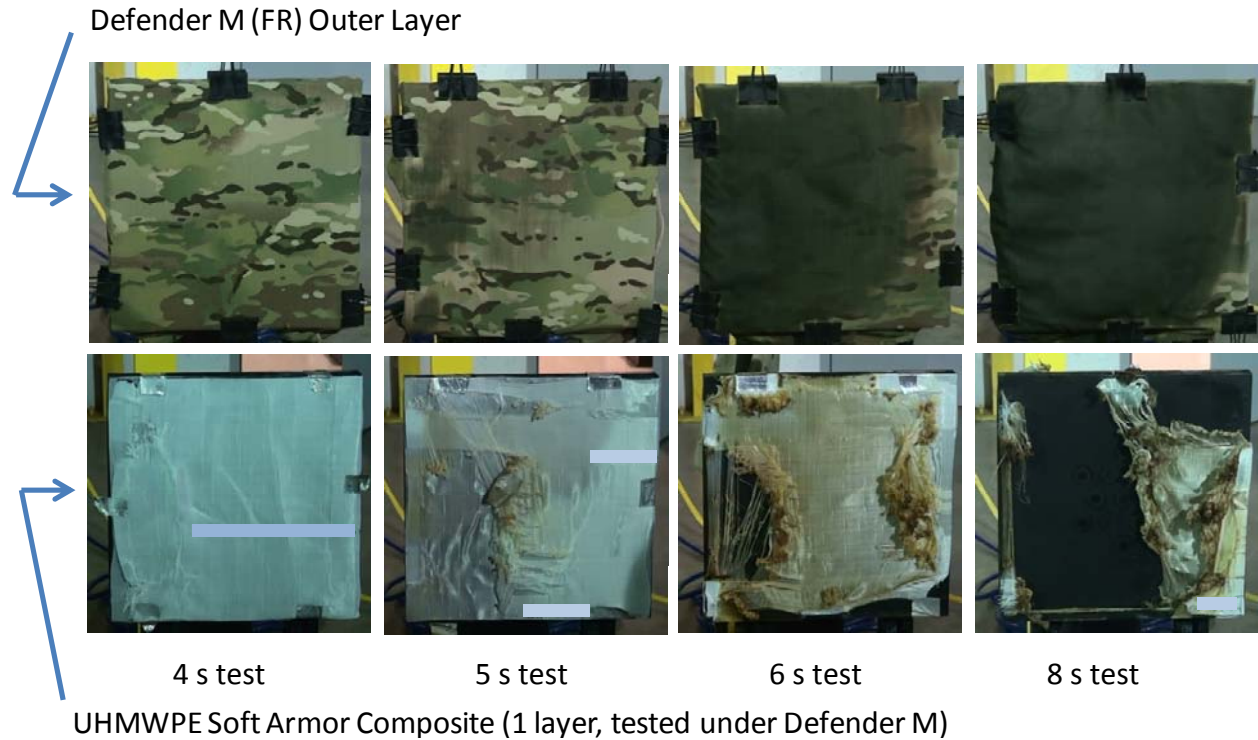
Figure 25. Flat panel midscale test of Defender M outer layer and UHMWPE composite (one layer) with increasing amounts of flash flame duration.

These results show a more progressive response to greater flame durations. The 4-s test showed only slight damage to the outer most ply of the UHMWPE composite. The 5-s test showed significant damage to the outer plies, while the inner plies remained intact. Significant damage to the composite material was observed after the 6-s test. The appearance of the melted and damaged area of the composite was quite different than in any of the UHMWPE fabric tests. Much of the material had melted and burnt away from the test panel after the 8-s test, exposing the heat flux sensors. A rapid increase in the transmitted heat flux was measured during the 8 s test, as shown in Figure 26.
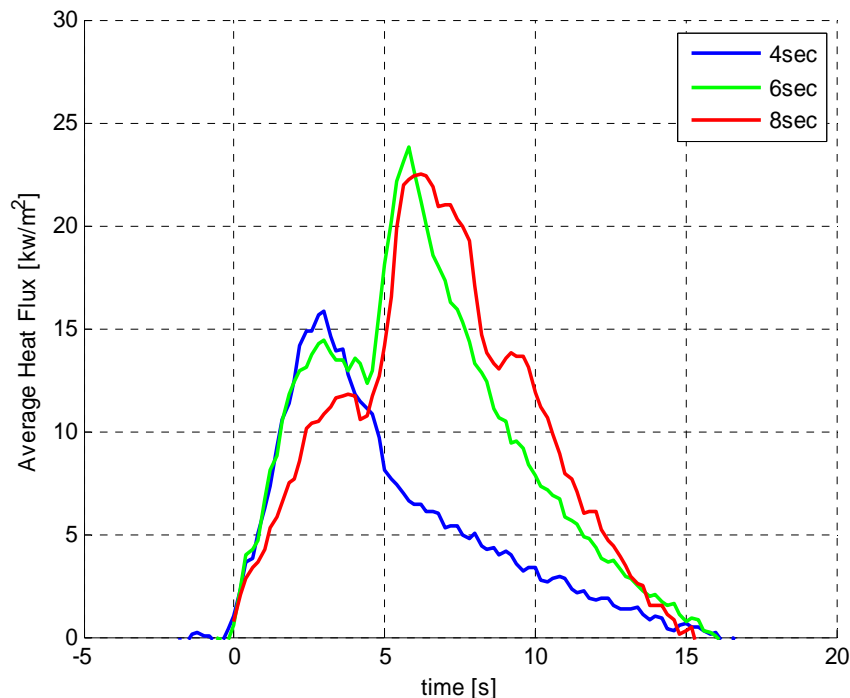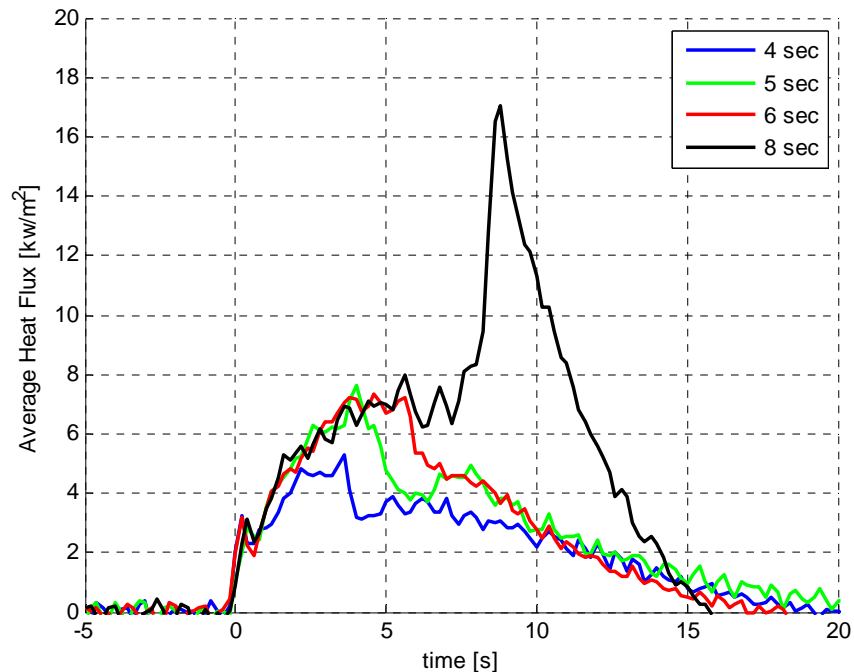
Figure 26. Flat panel midscale test heat flux transmitted through Defender M outer layer and UHMWPE composite (one layer) with increasing amounts of flash flame duration.

4.2.2.6 Comparison of UHMWPE Materials Response to Flat Panel Test

Each material showed some varying degree of thermal effects during the 6-s test. The condition of each UHMWPE fabric material after 6 s of flash flame is displayed in Figure 27.
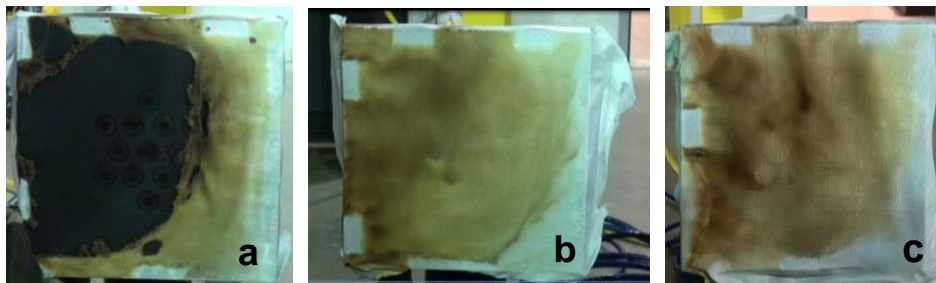
Figure 27. Flat panel midscale test of UHMWPE materials under Defender M outer layer after 6 s: a) UHMWPE 375D plain weave; b) UHMWPE 1200D plain weave; c) UHMWPE 650D knit.

The lighter weight UHMWPE 375D fabric clearly suffered the most significant damage in the 6-s test. This is also reflected in the transmitted heat flux overlay plot shown in Figure 28. Both the UHMWPE 1200D woven fabric and the UHMWPE 650D knit fabric showed some minor damage and distortion in the 6-s test. The 650D knit material showed a higher transmitted heat flux than the 1200D woven fabric, with approximately the same areal density. This could be due to the more open and permeable construction of this knit fabric.

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Comparison of Heat Flux through Materials, Outer Layer: Defender M
6 s duration. Heat Flux: 84kW/m^2
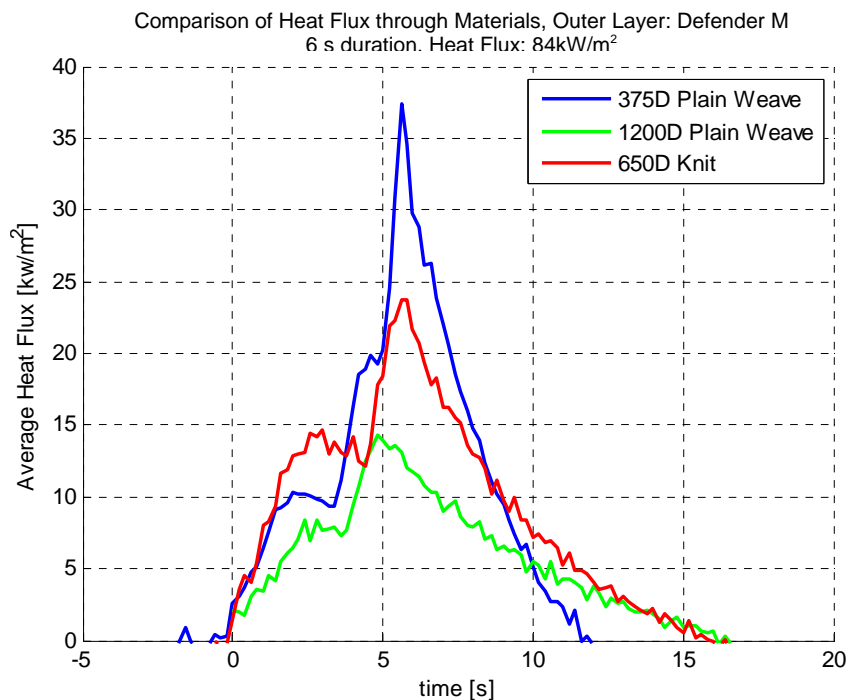
Figure 28. Flat panel midscale test heat flux transmitted through UHMWPE materials under Defender M outer layer after 6 s.

4.2.3 Summary of Midscale Test Results and Observations

The midscale test results showed that any direct flame on the UHMWPE materials will cause rapid disintegration of the material. These materials must be shielded by an FR material to prevent direct exposure to flames or high heat flux. The cylindrical midscale test showed the Defender M shielded the UHMWPE materials from the flame, but it became evident that the hot gasses were able to flow behind the Defender M, causing increased damage to the UHMWPE layer underneath. In the flat panel midscale test, this effect was prevented by clamping the material around all edges of the flat panel. The flat panel provided the most control and was used to test all of the layered material combinations.

In the 4-s flash flame duration test on the flat panel, with the Defender M layered over the UHMWPE material, no significant damage to either layer was observed. During these tests, the UHMWPE layer provided significantly more thermal protection, measured by the transmitted heat flux, than the Defender M fabric alone. The flat panel tests showed that between 4-s and 5-s of exposure to the calibrated 84 kW/m^2 heat flux the Defender M began to decompose and become charred. It was after this point that the UHMWPE layers began to show the thermal effects of the transmitted heat flux. The lighter weight UHMWPE 375D woven fabric began to melt and burn away from the flat panel in a 5-s test. The thicker UHMWPE 1200D woven fabric and 650D knit fabric did not show any significant damage until tested for longer than 6 s.

One test on the midscale cylinder was conducted to show the response of the UHMWPE materials to direct flame exposure. The UHMWPE fabric material did not

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show a typical melting and dripping response. Rather than melting into a liquid state, the yarns appeared to recoil into a shorter piece of material. The physical response of the UHMWPE fibers when exposed to heat could have implications in garment design which are different than concerns of melting and dripping thermoplastic material.

4.3 Thermal Manikin Test Results

A major difference between testing materials on the thermal manikin and the midscale flat panel is the amount of variability in the heat flux over the testing surface, measured by different sensors at different locations in the same test. The standard deviation in heat flux calibration tests on the manikin was at least twice the standard deviation from the same test on the midscale flat panel. (This variability is shown and explained in Appendix B.) For the tests on the thermal manikin, this means the materials were exposed to heat flux in some areas which was significantly higher than the average, while significantly lower in others.

Table 4 shows the total area of predicted burn injuries (for second degree, third degree, and total for both second and third) based the results of the ten thermal manikin tests. The single test of the Defender M coveralls with no undergarments showed a very high level of total burn injury at ~65%. All of the tests of the coveralls with any type of undergarment (UHMWPE or cotton) ranged from ~31 to 39% total burn injury. The total burn injury was reduced when FRACU was the outer layer, to ~20% when worn over cotton and ~17% when worn over UHMWPE 375D. It is important to consider that the head sensors were uncovered in all the tests, which accounts for 7% of the third degree burn injury. The predicted burn injury results at each sensor are shown in Appendix C.

Table 4. Thermal manikin burn injury prediction results.

		FR Outer Layer	Undergarments	2nd Degree (Area %)	3rd Degree (Area %)	Total (Area %)
Day 1	Test 1	Coveralls	None	43.6	20.9	64.5
	Test 2	Coveralls	UHMWPE 375D Woven	23.0	14.2	37.2
	Test 3	Coveralls	UHMWPE 1200D Woven	22.5	13.4	35.9
	Test 4	Coveralls	UHMWPE - 375D Woven	25.5	11.5	37.0
	Test 5	Coveralls	Cotton T-Shirt & Briefs	26.9	11.7	38.5
Day 2	Test 1	Coveralls	Cotton T-Shirt & Briefs	24.1	11.5	35.6
	Test 2	FRACU	Cotton T-Shirt & Briefs	10.5	9.9	20.5
	Test 3	FRACU	UHMWPE 375D Woven	8.4	8.9	17.3
	Test 4	Coveralls	UHMWPE 650D Knit	21.2	13.3	34.5
	Test 5	Coveralls	UHMWPE - 375D Woven	15.4	15.2	30.6

4.3.1 Manikin Test of Defender M Coveralls and FRACU

A single test of the Defender M coveralls was conducted to observe its response in the flash flame environment and measure the heat shielding it will provide to the various

UHMWPE undergarments. A photograph of the front and back of the coverall after the test in the 4-s flash flame test is shown in Figure 29.

Figure 29. Manikin Test of Defender M coveralls tested with no undergarments.

A significantly greater amount of after-flame and char to the Defender M material was observed on the manikin immediately after the 4-s test than was observed after 4.5 s in the midscale flat panel tests (as shown in Figure 18). One reason for the increased damage in the 4-s manikin test is the increased variability and "hot spots" that were present around the manikin. Another reason could be the difference in boundary conditions behind the Defender M fabric. On the flat panel apparatus, the fabric was clamped around the panel, with significant contact between the material and the panel surface. This could allow the flat panel to absorb more energy from the fabric through conduction during the test and reduce the temperature rise in the fabric. On the thermal test manikin, the material contact between the back side of the material and the manikin surface was much more complex, and dependent on the fit of the garment. If the fabric is not in contact with the manikin surface, heat cannot be removed from the fabric through conduction, and the fabric temperature will increase at a faster rate.

Because Ouellette TTF normally conducts the ASTM F1930 test with cotton undergarments (T-shirt and briefs), the Defender M coveralls were also tested with cotton undergarments in order to compare with the transmitted heat flux of the UHMWPE undergarments. Two tests were conducted in this configuration. The condition of the cotton fabric after the test (and after removal of the Defender M coverall) is shown in Figure 30. There were differences in the area covered by the UHMWPE undergarments and the area covered by the cotton briefs and T-shirt, which is described in Section 3.2.2

Figure 30. Condition of cotton undergarments under Defender M coveralls after manikin test.

Due to the greater damage of the Defender M material on the thermal test manikin than on the flat panel, the test plan included two tests with the FRACU (pants and shirt), so the results could be compared with the coveralls. One of these FRACU tests was conducted with the cotton undergarments, and the other was conducted with a set of the UHMWPE undergarments. The condition of the FRACU before and after one of these tests is shown in Figure 31.

Figure 31. Manikin test of FRACU: a) Before testing; b) After testing.

The tests conducted with the Defender M coveralls (no undergarments and with cotton undergarments) and the test with the FRACU (cotton undergarments) provide a baseline to compare with the testing of the UHMWPE undergarments. A comparison of these tests is displayed in Figure 32 between the area to be covered by the UHMWPE fabric shorts and the area to be covered by the cotton briefs. The cotton undergarments provided two layers of cotton over the sensors (briefs and cotton T-shirt hanging over the briefs). Figure 33 shows the comparison of these tests in the vest area.
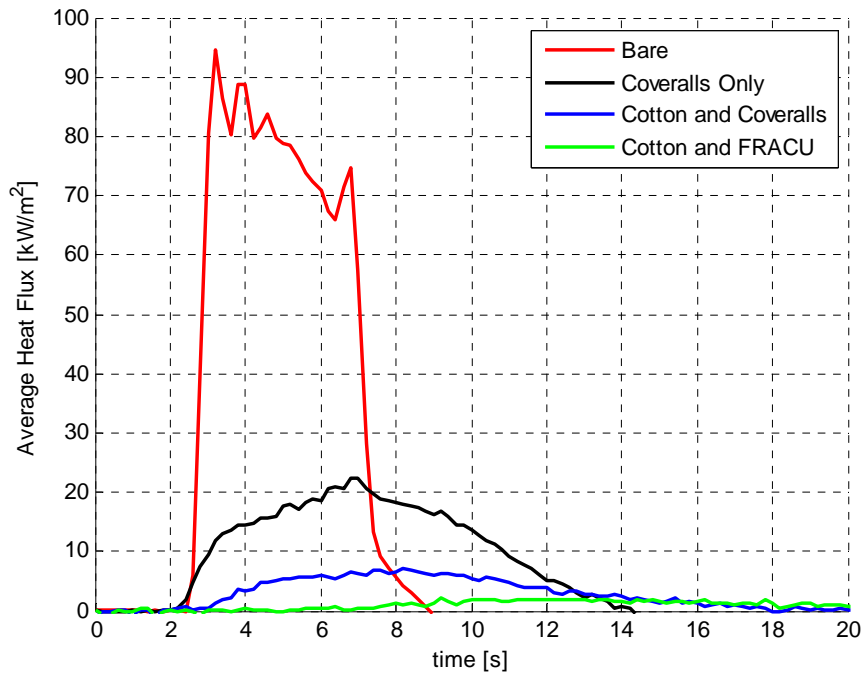
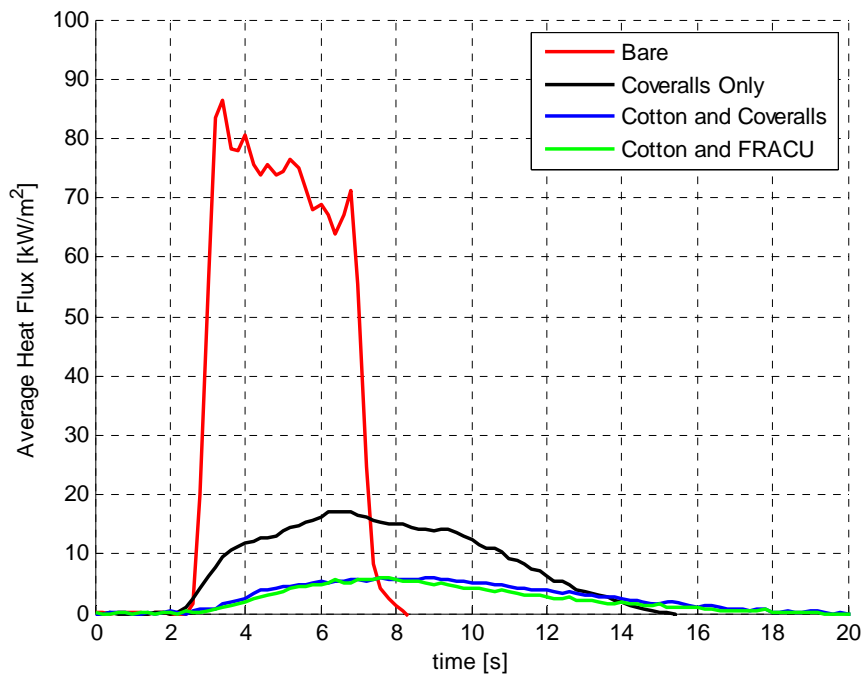**Figure 32. Manikin test baseline heat flux levels in briefs area.**

Figure 33. Manikin test baseline heat flux levels in vest area.

The reduction in transmitted heat flux provided by the Defender M coveralls is apparent between the bare condition and the coveralls with no undergarments. In both areas on the manikin (briefs and vest area), the cotton undergarments provided a significant reduction in the transmitted heat flux when they were worn underneath the coverall. In the vest area, the transmitted heat flux underneath the coverall and cotton T-shirt was almost identical to the FRACU with cotton T-shirt. In the briefs area, the FRACU

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showed lower heat flux than the coverall. This is likely a result of the multiple fabric layers that are used in the pockets and other design features in the shorts area of the FRACU pants, as well as the additional layer where the shirt is tucked into the pants.

4.3.2 Manikin Test of UHMWPE 375D Woven Undergarments

A total of four tests were conducted with the UHMWPE 375D woven shorts and vest, three underneath the Defender M coveralls and one underneath the FRACU. Observed damage to UHMWPE fabrics varied between the tests.

Photographs of the front and back of the UHMWPE undergarments after the first of the tests with the Defender M coveralls are displayed in Figure 34. This test was conducted with the vest tucked into the shorts, while all other tests of UHMWPE 375D garments were conducted with the vest hanging over the shorts. The UHMWPE fabric showed some damage after the test. In these damaged areas some material had hardened, which is evidence of melting and re-solidifying. Around these areas, there was deformation and shrinking of the structure. The damage did not include any holes in the UHMWPE fabric, in this or any other manikin test. The area around the shorts, particularly the right front thigh and the left buttock, showed more significant damage in this test, as shown by the close-up photographs in Figure 35. This could be a result of a higher incident heat flux from the propane flames or could be related to the fit of the shorts in this area on the manikin. As indicated in Table 4, the total burn injury area was similar in the second test under the coveralls, but the severity was slightly less, i.e., a smaller proportion of third degree burns.

Figure 34. Manikin test of UHMWPE 375D woven fabric under Defender M coveralls on Day 1.

Figure 35. Close up of manikin test damage to UHMWPE 375D woven shorts.

The third test of the UHMWPE 375D woven undergarment with the Defender M coveralls, which was conducted on a second day of testing and after the test of the 375D fabric under the FRACU, resulted in less overall damage to the material than the two previous tests, as shown in Figure 36. The right thigh area of the UHMWPE shorts also showed the most damage in this test. The total predicted burn injury was 30.6% in this test, compared to an average of 37.1% for the two tests on day 1. This is a proportional reduction of approximately 18% between these tests. (Note: This is within the +/- 21% repeatability for a similar material test as reported by ASTM F1930 with a repeatability limit of 9.2% total burn injury for an average total burn injury of 43.6%.) (10).

Figure 36. Manikin test of UHMWPE 375D woven fabric under Defender M coveralls on Day 2.

As was expected, due to the additional fabric layers of the FRACU garments, the UHMWPE 375D undergarments showed significantly less overall damage in the test under the FRACU pants and shirt on the manikin than any of the tests under the

coveralls. This was especially true in the shorts, where the only visible damage was near the bottom hem of the right leg. The condition of these undergarments after the test is shown in Figure 37.

Figure 37. Manikin test of UHMWPE 375D woven fabric tested under FRACU.

The additional thermal protection of the FRACU in the shorts area is also evident by a reduction in transmitted heat flux by almost one half, in comparison to the tests under the Defender M coveralls. The average heat flux in the UHMWPE 375D woven briefs and vest area for each test is displayed in Figure 38 and Figure 39, respectively.
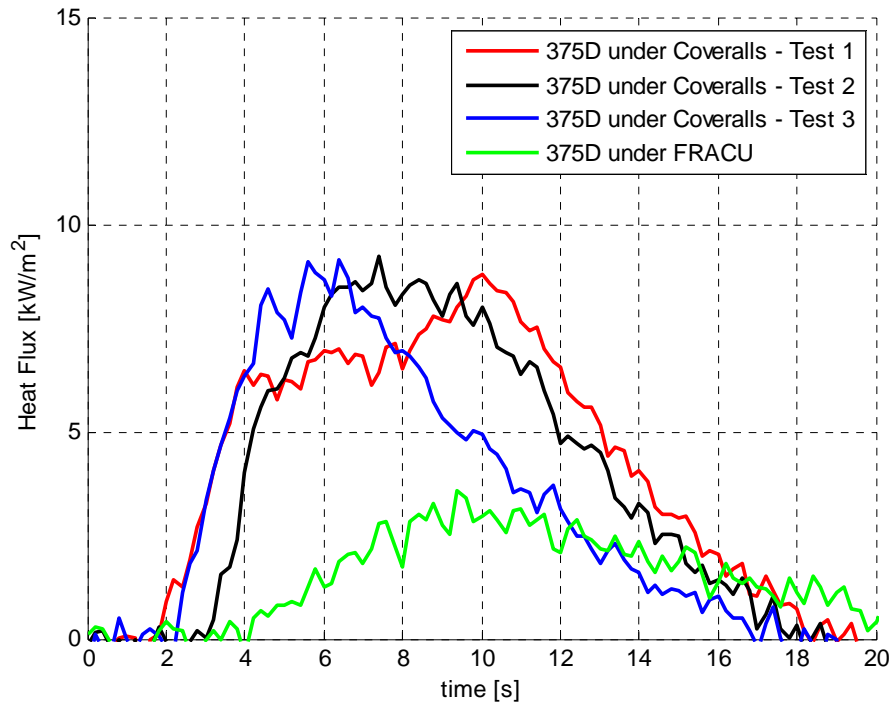
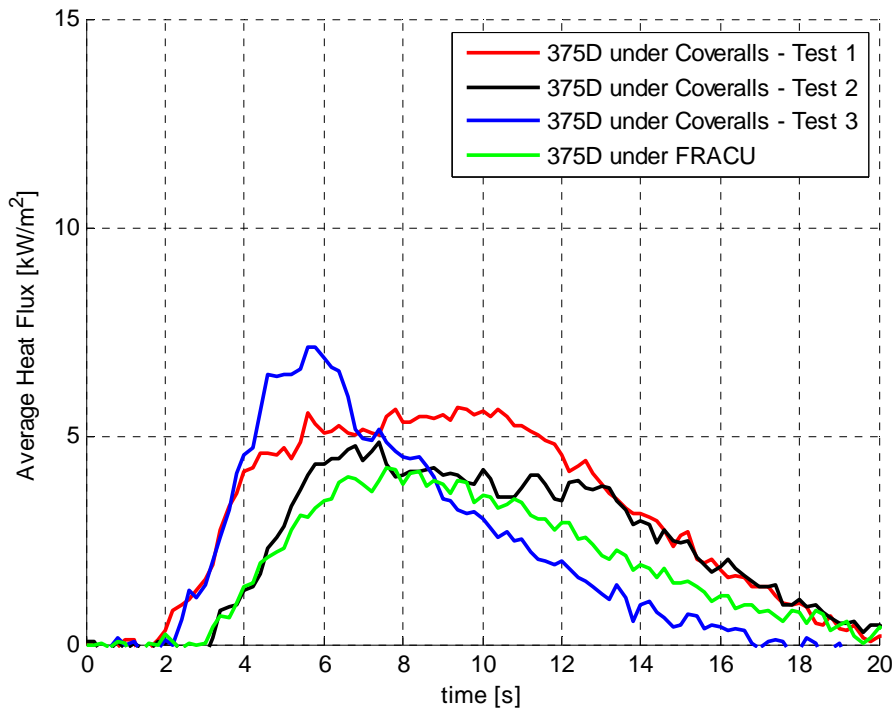**Figure 38. Comparison of manikin tests of UHMWPE 375D plain weave briefs area.**

Figure 39. Comparison of manikin tests of UHMWPE 375D plain weave in vest area.

4.3.3 Manikin test of UHMWPE 1200D Woven and 650D Knit Undergarments

A single set of the UHMWPE 1200D woven undergarments and a single set of the 650D knit undergarments were tested on the thermal manikin under the Defender M coveralls.

These heavier garments showed less damage than the lighter 375D woven fabric. The condition of the 1200D undergarments after testing is shown in Figure 40. The right thigh showed more damage again in this test, as displayed in the close up of the shorts area in Figure 41. The 650D knit material showed the least amount of visible damage of any of the UHMWPE fabrics tested underneath the coveralls, as shown in Figure 42.

Figure 40. Manikin test of UHMWPE 1200D plain weave under Defender M coveralls.

Figure 41. Close up of manikin damage to UHMWPE 1200D plain weave shorts.

Figure 42. UHMWPE 650D knit tested underneath Defender M coveralls.

4.3.4 Manikin Test Heat Flux Transmitted Through All Undergarments

The average transmitted heat flux in the briefs area in tests with each of the different undergarment materials is overlaid in Figure 43. The heaviest UHMWPE fabric was the 1200D woven material, and accordingly, it showed the greatest reduction in transmitted heat flux of the materials tested under the Defender M coveralls. The 375D woven and 650D knit materials tested under the coveralls showed an average heat flux over this area that was similar to that measured under the cotton undergarments tested under the coveralls, but the cotton undergarments provided two layers of cotton over the sensors (cotton T-shirt hanging over the briefs).
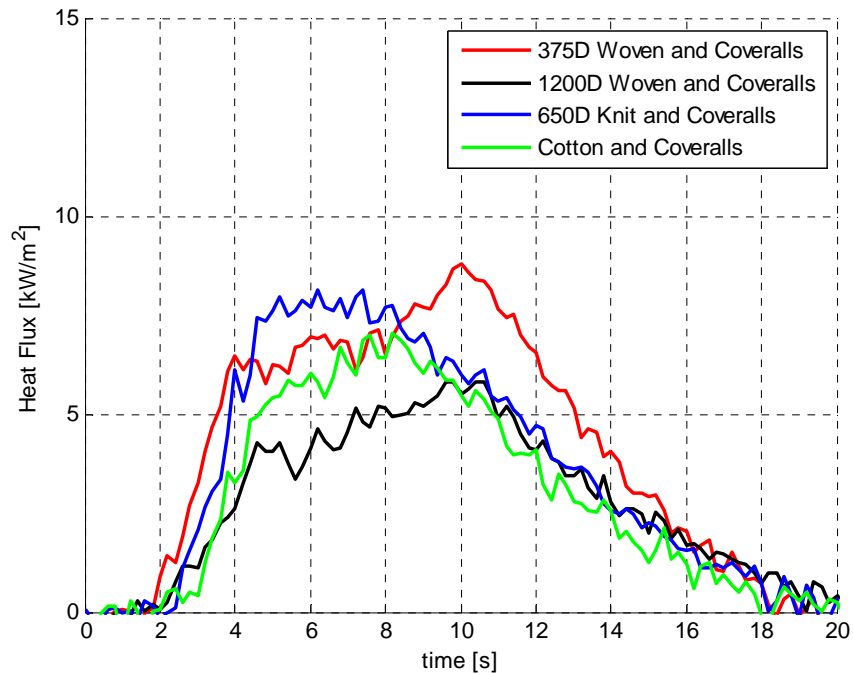
Figure 43. Manikin test heat flux transmitted through all materials in briefs area.

The average transmitted heat flux in the vest area is very similar for the 375D woven, which is the lightest of the UHMWPE fabrics, and the cotton knit T-shirt. The heavier UHMWPE fabrics (1200D woven and 650D knit) show a reduced average transmitted heat flux in the vest area, as shown in Figure 44.
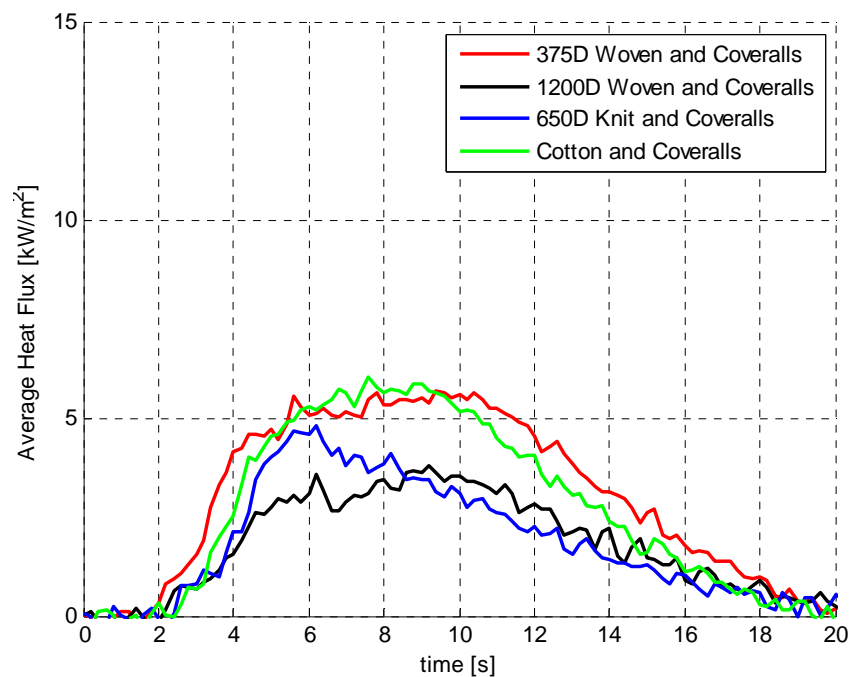

Figure 44. Manikin test heat flux transmitted through all materials in vest area.

The average values may mask some of the effects of materials on the transmitted heat flux, indicated by the localized damage seen in some areas of the UHMWPE fabric on the test manikin. For example, the materials that covered the left buttock sensor (number 116) showed significant burn injury in many of the tests. However, this sensor protruded slightly from the manikin surface, which would increase its contact with the undergarments. The heat flux from this sensor for all the undergarment tests is plotted in Figure 45. As can be seen, the highest transmitted heat flux at sensor 116 was measured in the tests with the UHMWPE 375D woven undergarments. However, a direct comparison cannot be made between these measurements and those for the cotton undergarments because two layers of cotton undergarments (i.e., the T-shirt hanging over the briefs) covered the sensor during testing. It is worth noting that the UHMWPE 1200D woven fabric (which has the areal density equivalent to approximately two layers of the 375D fabric) had a lower transmitted heat flux than the two layers of cotton fabric that covered sensor 116 in these tests. As expected, the tests with the FRACU showed lower transmitted heat flux at this sensor than those with the coveralls. These data are provided for additional insight into the material response, although an assessment of material performance cannot be made from from analysis of one sensor.
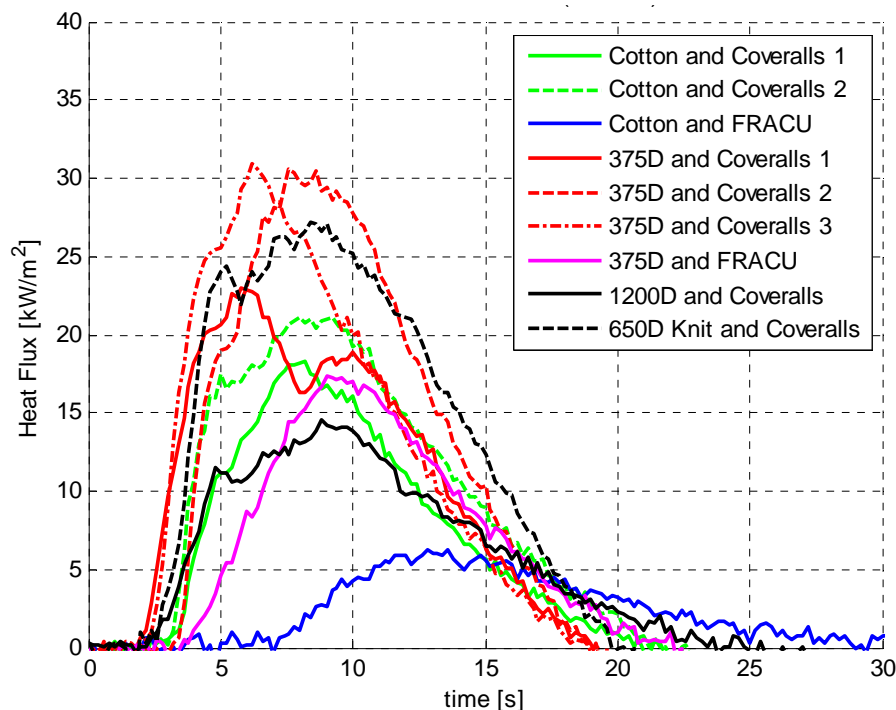

Figure 45. Manikin test heat flux transmitted in all tests at left buttock sensor.

4.3.5 Summary of Manikin Test Results and Observations

Undergarments of any kind reduced transmitted heat flux and predicted burn injury. The heavier UHMWPE undergarments showed a greater reduction in transmitted heat flux, as would be expected with any material. There was no increase in the average measured heat flux or calculated burn injury when the thermal test manikin was wearing the UHMWPE test garments as compared to the cotton undergarments. For the total

burn injury predictions, this comparison is hampered slightly by difference in area coverage between the cotton undergarments and the UHMWPE undergarments.

In each of the six tests with the UHMWPE fabric undergarments on the thermal test manikin, some damage was observed in the undergarments. This damage was a localized deformation of the fabric, where some of the material had solidified into a hardened plastic area. Around these areas of hardened plastic, the fabric was distorted by apparent pulling in other yarns in the local area. This deformation could pull the fabric closer to the skin, increasing the chance of thermal injury due to conductive heat transfer, although this was not measured on the thermal test manikin in these tests. There were no instances of the material melting and dripping. All of the UHMWPE test garments were intact (no holes or burnt material) after testing underneath the shielding of the Defender M fabric coveralls or FRACU.

5 Conclusions

UHMWPE is a high performing material in the application of ballistic protection. However, it is also a thermoplastic material known to have a low melting point (approximately 135 -150 °C). For this reason there are concerns with its use in a garment or piece of protective gear that could be exposed to a high heat environment. This study addressed some of those concerns with thermal testing of UHMWPE fabrics and test garments.

As was expected, preliminary testing with the vertical flame and midscale flash flame testing showed that the UHMWPE fabric must be shielded from direct flames, or it will be rapidly destroyed and consumed. A range of testing was conducted at the NSRDEC Ouellette TTF to evaluate the response of UHMWPE fabrics and composite material in a flash flame environment, when shielded by the Defender M flame resistant fabric. This included vertical flame testing, midscale flash flame testing, and flash flame testing according to ASTM F1930 with the thermal test manikin.

When shielded by the Defender M fabric, the UHMWPE fabrics and composite withstood the flash flame environment in the midscale flat panel test for a 4-s flame duration, with almost no damage. The UHMWPE materials were fabricated into undergarments and tested beneath a Defender M coverall, as well as a FRACU, on the thermal manikin. After exposure to 4-s flash flame, the undergarments showed some damage, with a localized hardening of the fabric material, where it appeared to have melted and re-solidified. This caused the fabric structure to deform and shrink around these areas. Despite this damage, the UHMWPE undergarments remained intact and did not burn when shielded by the Defender M fabric. There was no significant difference in the total burn injury predicted from the test data between the cotton undergarments or the UHMWPE undergarments.

The results show that it may be possible to incorporate UHMWPE materials in a protective garment (such as the PUG) and still provide the FR performance required to pass the ASTM F1930 flash flame manikin test. This would include designing the garment so that the UHMWPE material would always be shielded from a direct flame. The potential effects of the fabric shrinkage and deformation remain a concern. The tradeoff between the potential increase in ballistic protection provided by the UHMWPE materials and the concerns with FR performance of these materials should be considered to maximize Soldier protection.

6 References

1. **Marissen, Roelof.** "Design with Ultra Strong Polyethylene Fibers." *Materials Sciences and Applications*, 2011, pp. 319-330.
2. **Honeywell.** "Honeywell Advanced Fibers and Composites." *Fibers.* [Online] [Cited: September 10, 2013.] http://www.honeywell-advancedfibersandcomposites.com/products/fibers/.
3. **DSM.** "Dyneema Formats and Applications." [Online] [Cited: September 10, 2013.] www.dyneema.com/americas/explore-dyneema/formats-and-applications.aspx.
4. **Petrilli, Tony.** *Tests of Undergarments Exposed to Fire.* Missoula, MT: US Department of Agriculture - Forest Service, 2008.
5. **Lance Cpl. Holt, Stephen, USMC.** "Synthetic Clothes Off Limits to Marines Outside Bases in Iraq." *News - American Forces Press Service.* [Online] April 12, 2006. [Cited: September 10, 2013.] http://www.defense.gov/News/NewsArticle.aspx?ID=15478.
6. **Lopez, C. Todd.** "'Kevlar Underpants' Protect Pelvic Region." *The Official Homepage of the US Army.* [Online] February 22, 2012. [Cited: September 10, 2013.] http://www.army.mil/article/74306/.
7. **Department of the Army.** *Statement of Work, Pelvic Protection System, Tier I Protective Under Garments (PUG).* 2012.
8. **ASTM International.** *D6413: Standard Test Method for Flame Resistance of Textiles (Vertical Test).* West Conshohocken, PA, 2012.
9. **ASTM International.** *F1358: Standard Test Method for Effects of Flame Impingement on Materials Used in Protective Clothing Not Designated Primarily for Flame Resistance.* West Conshohocken, PA, 2008.
10. **ASTM International.** *F1930: Standard Test Method for Evaluation of Flame Resistant Clothing for Protection Against Fire Simulations Using an Instrumented Manikin.* West Conshohocken, PA, 2012.
11. **TenCate Protective Fabrics.** "TenCate Defender M." [Online] [Cited: 6 2, 2014.] http://www.tencate.com/emea/Images/EN_DM921028-24348.pdf.
12. **Barker, Roger L.** *Review and Evaluation of Thermal Sensors for Use in Testing Firefighters Protective Clothing.* Gaithersburg, MD: US Department of Commerce, National Institute of Standards and Technology, 1999.

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Appendix A
Clamping of Material on Flat Panel Midscale Test

Preliminary flat panel tests of the UHMPWE 375D fabric under the Defender M fabric were conducted using three different clamping configurations to demonstrate the effect of the location and number of clamps used, as shown in Figure A-1, and determine the configuration that provides the most control. The worst performance was when the material was clamped only on the two opposite side edges of the flat panel (Figure A-1a). There was significantly more charring of the Defender M outer layer and significantly more damage to the UHMWPE 375D plain weave under layer with this configuration than with the others. The damage to the UHMWPE material was most severe on the bottom edge of the fabric, as was the case in the cylindrical midscale test. Figure A-1b shows the results with the material clamped only on the top and bottom of the flat panel, where there was more damage to the fabric materials on the side of the flat panel. When the material was clamped on all four sides, as shown in Figure A-1c, there was no damage to the Defender M outer layer or the UHMWPE 375D woven under layer. These preliminary tests highlight the importance of preventing any open edges from allowing ingress of the flames and hot gasses during the test. Thus the planned flat panel tests of all the materials were conducted with the materials clamped on all four sides.

a **b** **c**
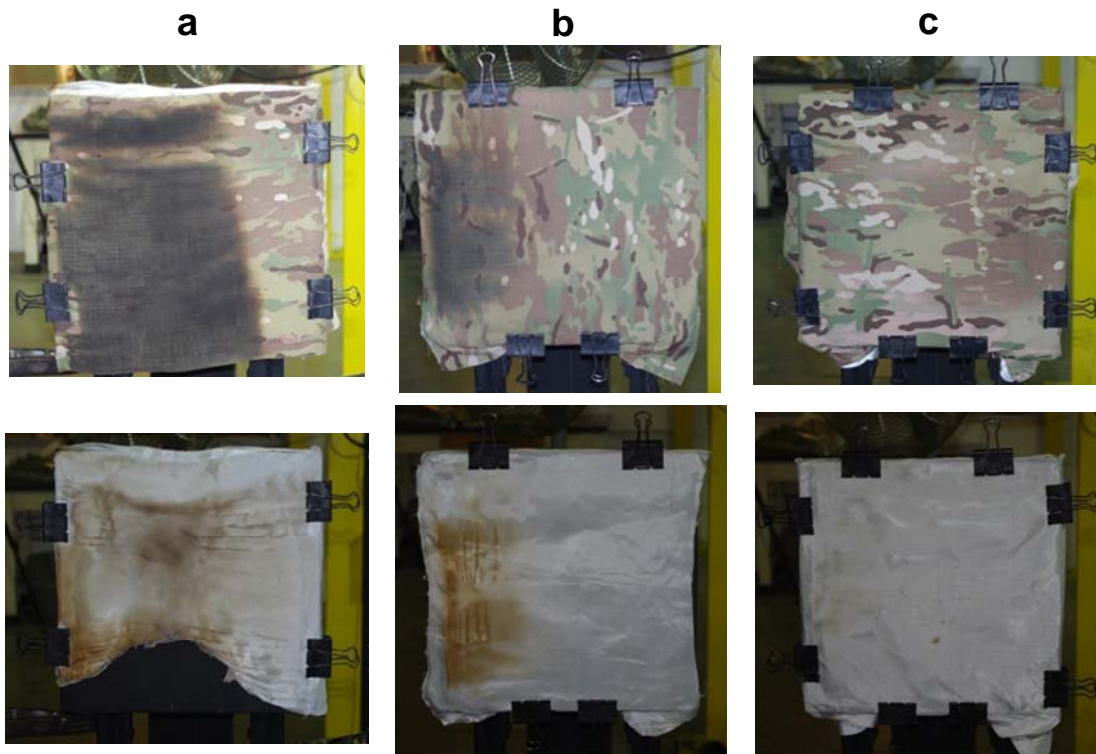
Figure A-1. Flat panel midscale test of Defender M and UHMWPE 375D with different clamping configurations: a) On two opposite sides only; b) On top and bottom only; c) On all four sides.

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Appendix B
Variability in Calculated Heat Flux

The variability in calculated heat flux between the sensors (which had no materials covering them) in the midscale flat panel test is shown, in Figure B-1, by plotting the average heat flux over the 13 sensors, the sensor with the highest and lowest average heat fluxes, and the standard deviation of the 13 sensors over time. Because materials were tested on two areas of the manikin (briefs area and vest area), as shown on the test manikin in Figure 9, the data from the manikin test sensors are grouped separately for the shorts (15 sensors total) and vest (33 sensors total) in Figure B-2 and Figure B-3, respectively. For a calibration burn (target of 84 kW/m^2 for 4-s), both figures show the average heat flux, high and low sensor heat flux, and standard deviation of the sensors located in the area where the materials will be worn.
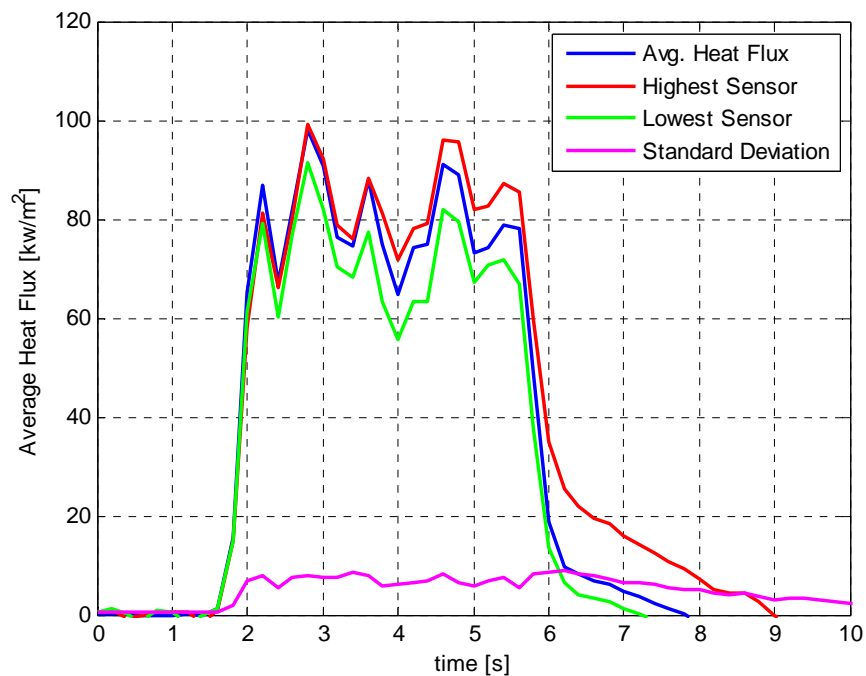
Figure B-1. Midscale flat panel calibration test.
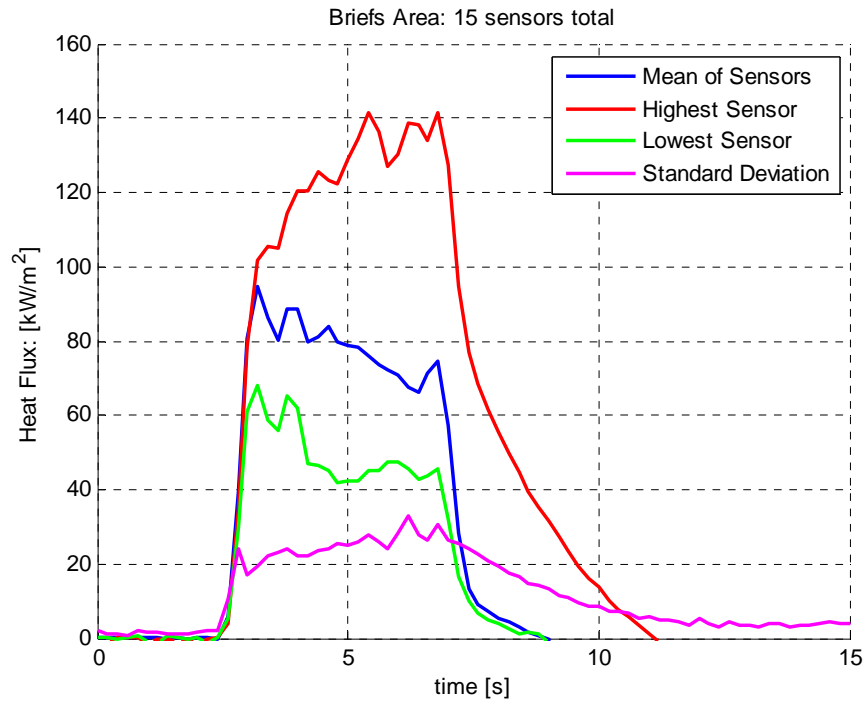
Figure B-2. Thermal manikin calibration test of briefs area.
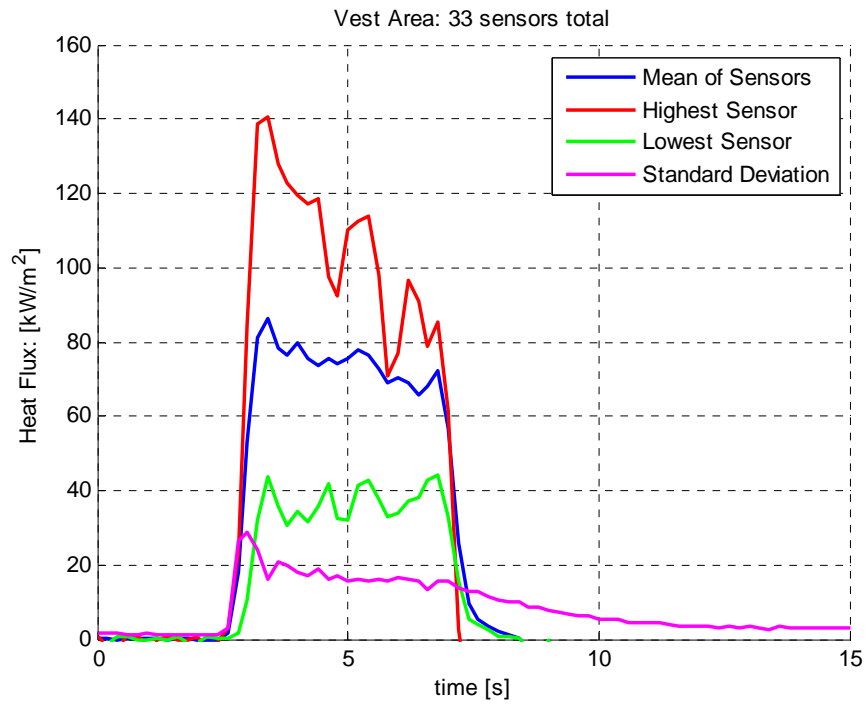
Figure B-3. Thermal manikin calibration test of vest area.

Appendix C
Sensor Display of Manikin Predicted Burn Injury Data

The predicted burn injury results at each sensor for each of the garment configurations evaluated in each of the 10 manikin tests (listed in Table 4) are shown in Figures C-1 through C-10, respectively.
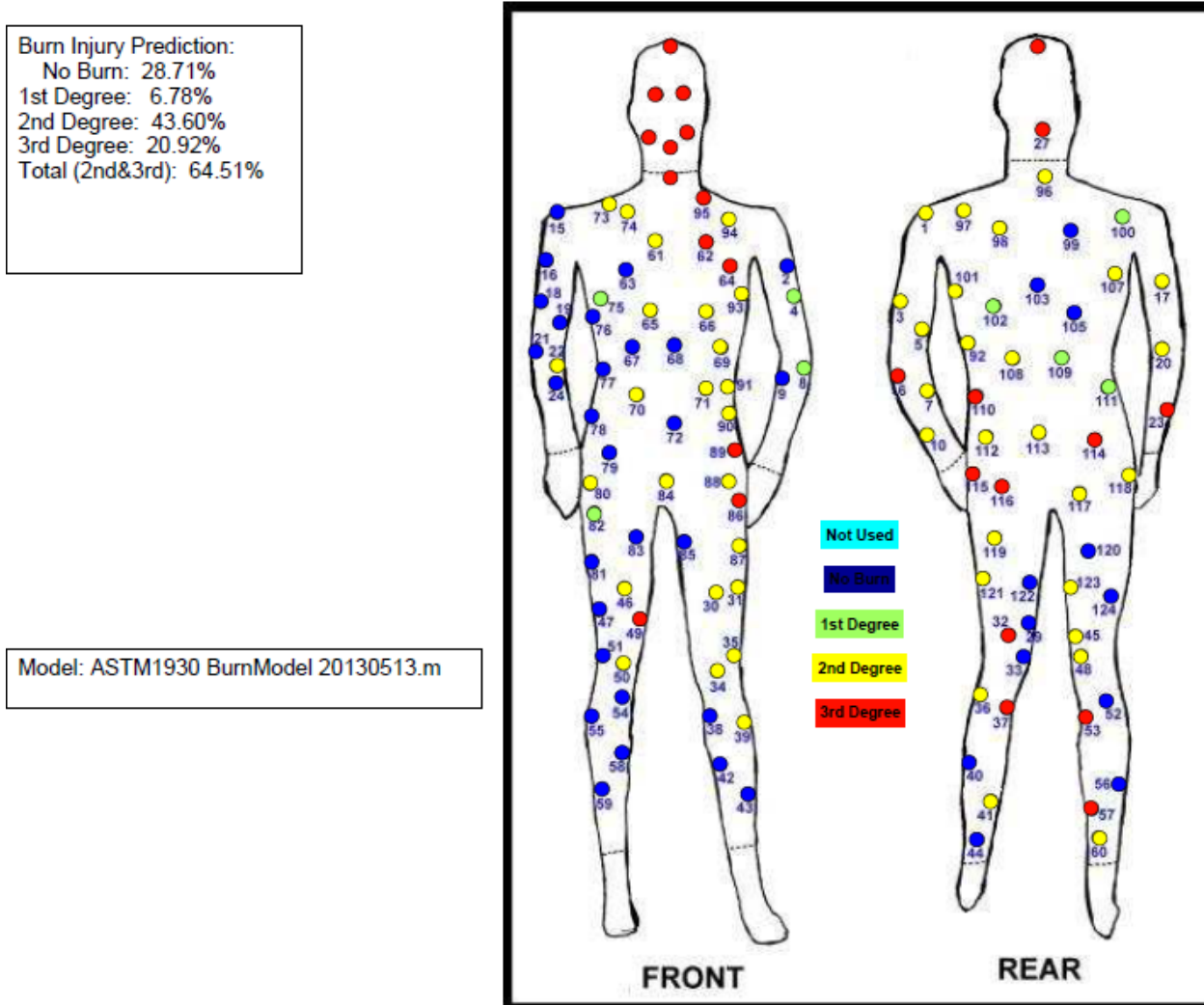

Figure C-1. Burn injury prediction Defender M coveralls with no undergarments.

Burn Injury Prediction:
 No Burn: 55.21%
1st Degree: 7.58%
2nd Degree: 23.01%
3rd Degree: 14.20%
Total (2nd&3rd): 37.21%
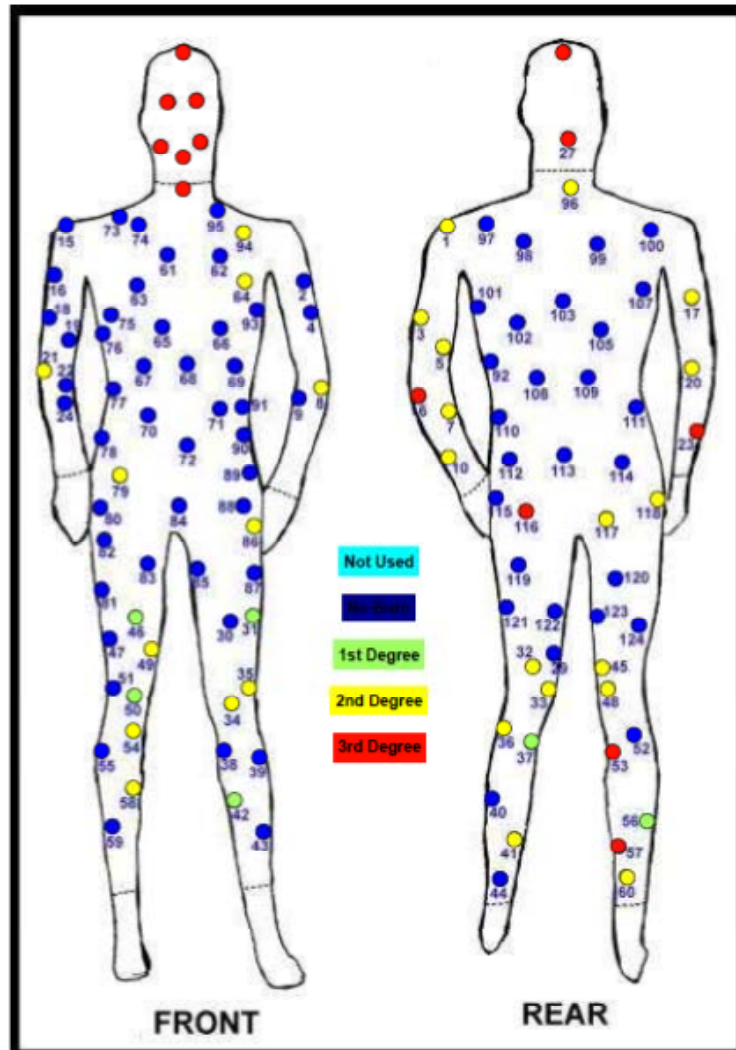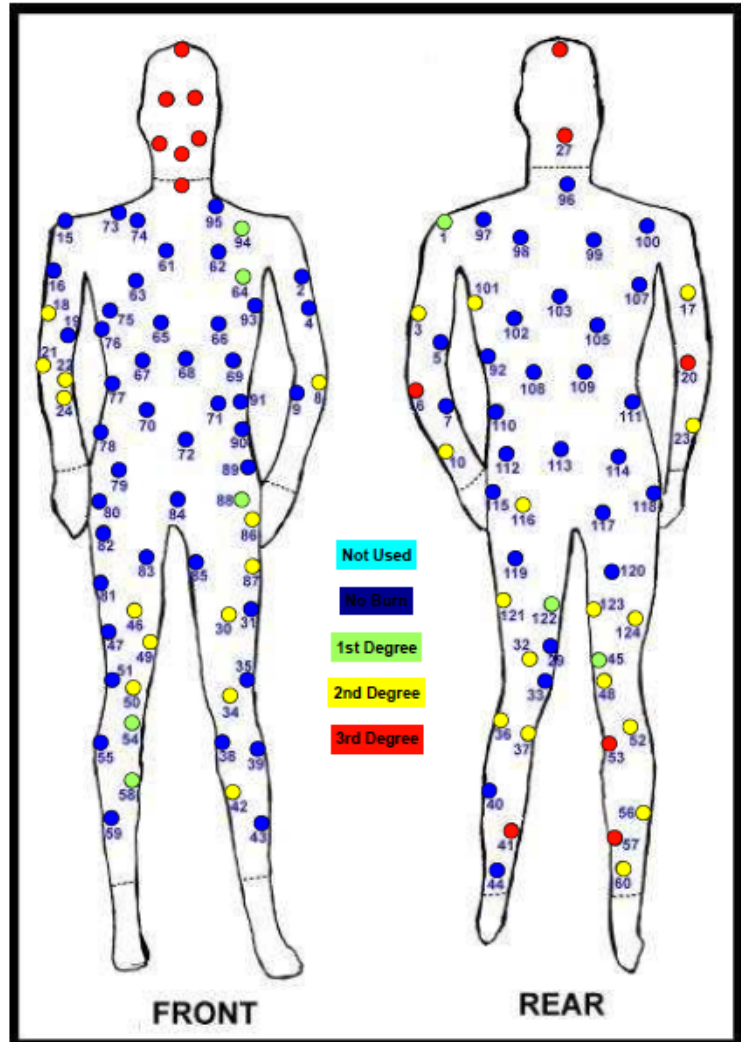
Model: ASTM1930 BurnModel 20130513.m
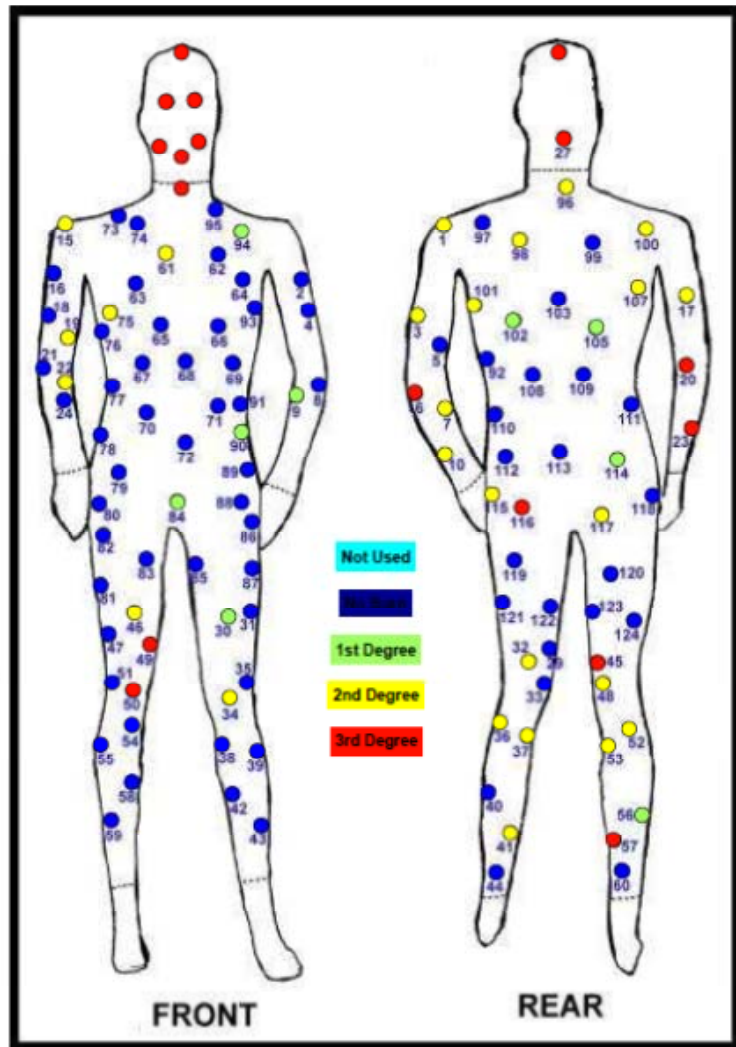
Figure C-2. Burn injury prediction for Defender M coveralls with UHMWPE 375D woven undergarments.

Burn Injury Prediction:
No Burn: 58.82%
1st Degree: 5.25%
2nd Degree: 22.53%
3rd Degree: 13.40%
Total (2nd&3rd): 35.93%

Model: ASTM1930 BurnModel 20130513.m
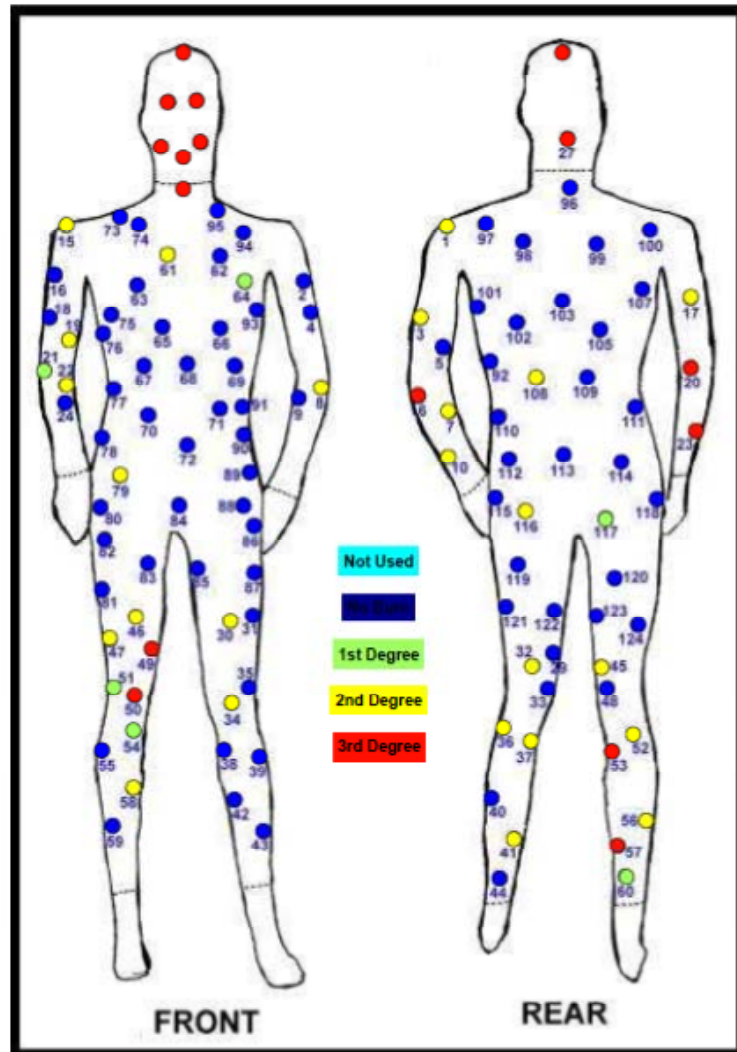
Figure C-3. Burn Injury Prediction of Defender M coveralls with UHMWPE 1200D woven undergarments.

Burn Injury Prediction:
    No Burn: 57.18%
1st Degree: 5.81%
2nd Degree: 25.49%
3rd Degree: 11.52%
Total (2nd&3rd): 37.00%

Model: ASTM1930 BurnModel 20130513.m

Figure C-4. Burn injury prediction: Defender M coveralls with UHMWPE 375D woven undergarments.
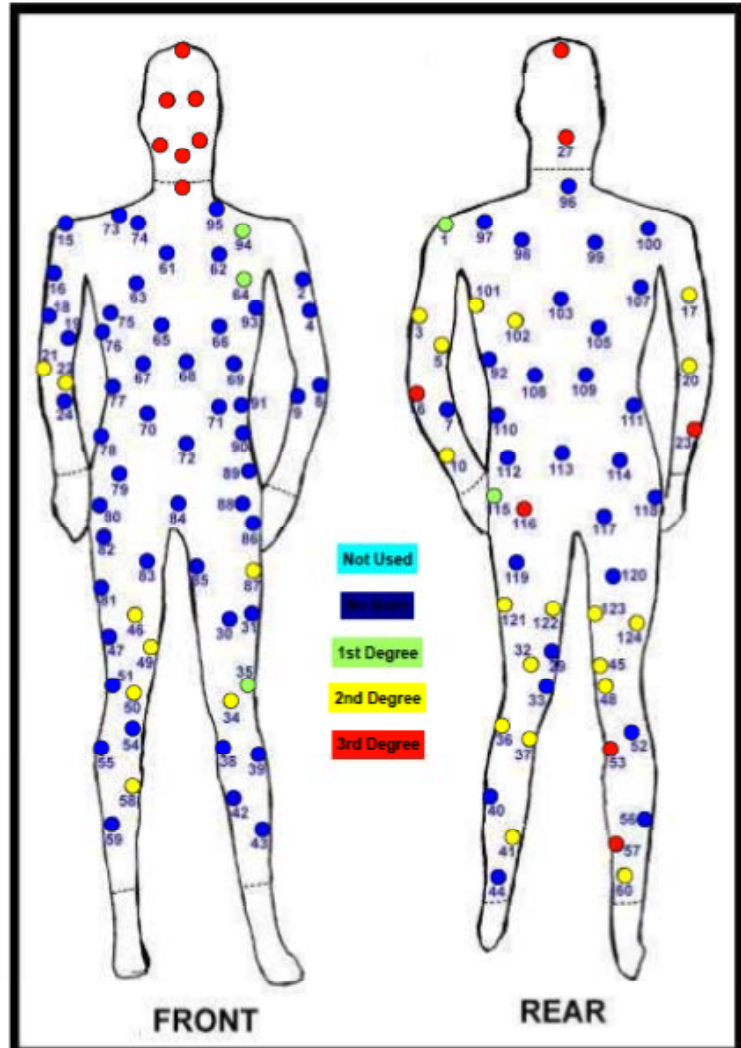
Figure C-5. Burn injury prediction: Defender M coveralls with cotton undergarments.

Burn Injury Prediction:
No Burn: 60.09%
1st Degree: 4.29%
2nd Degree: 24.11%
3rd Degree: 11.52%
Total (2nd&3rd): 35.63%
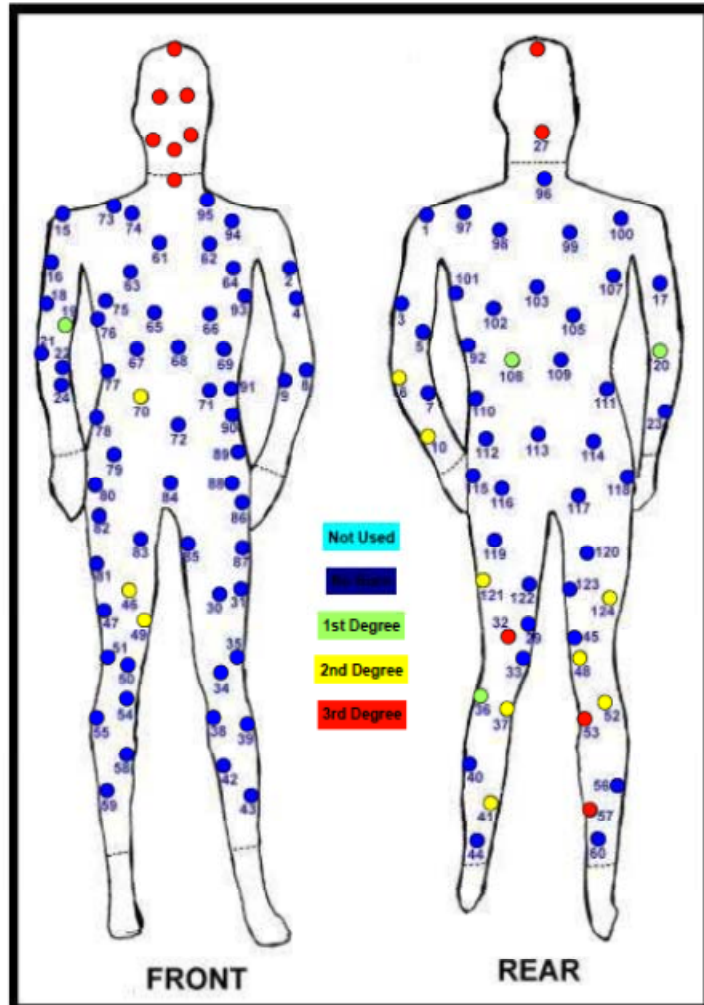
Model: ASTM1930 BurnModel 20130513.m

Figure C-6. Burn injury prediction: Defender M coveralls with cotton undergarments.

Figure C- 7. Burn injury prediction: FRACU with cotton undergarments.

Burn Injury Prediction:
No Burn: 80.86%
1st Degree: 1.80%
2nd Degree: 8.40%
3rd Degree: 8.94%
Total (2nd&3rd): 17.34%

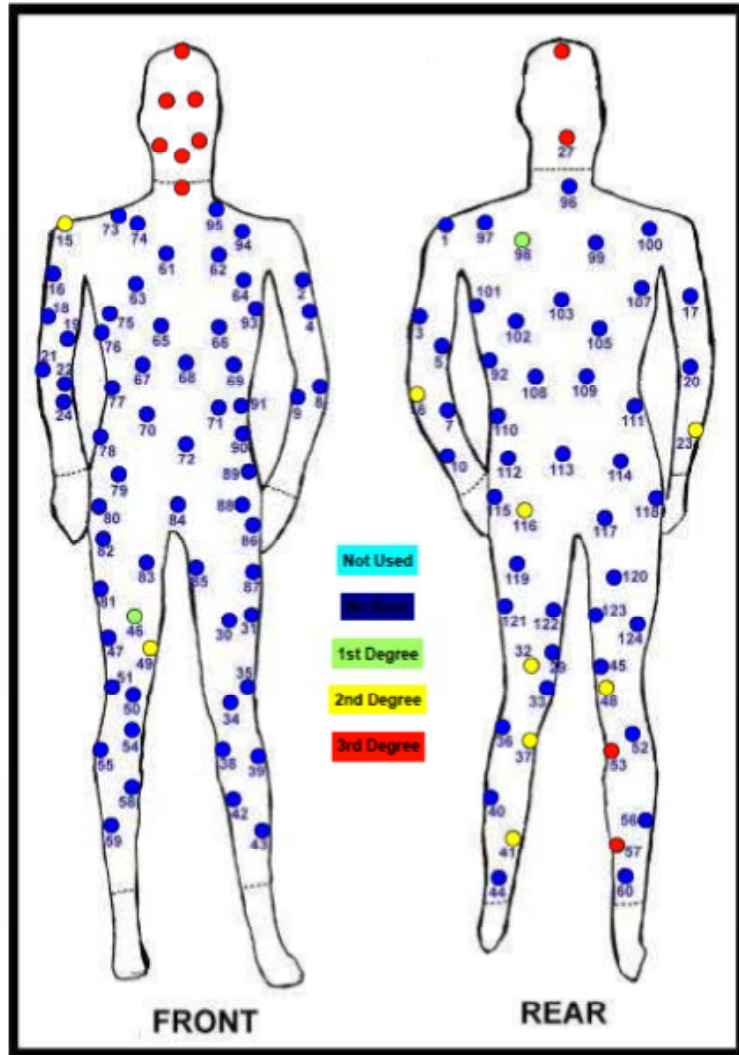Model: ASTM1930 BurnModel 20130513.m

Figure C-8. Burn injury prediction: FRACU with UHMWPE 375D woven undergarments.

Burn Injury Prediction:
   No Burn: 59.10%
1st Degree: 6.38%
2nd Degree: 21.18%
3rd Degree: 13.34%
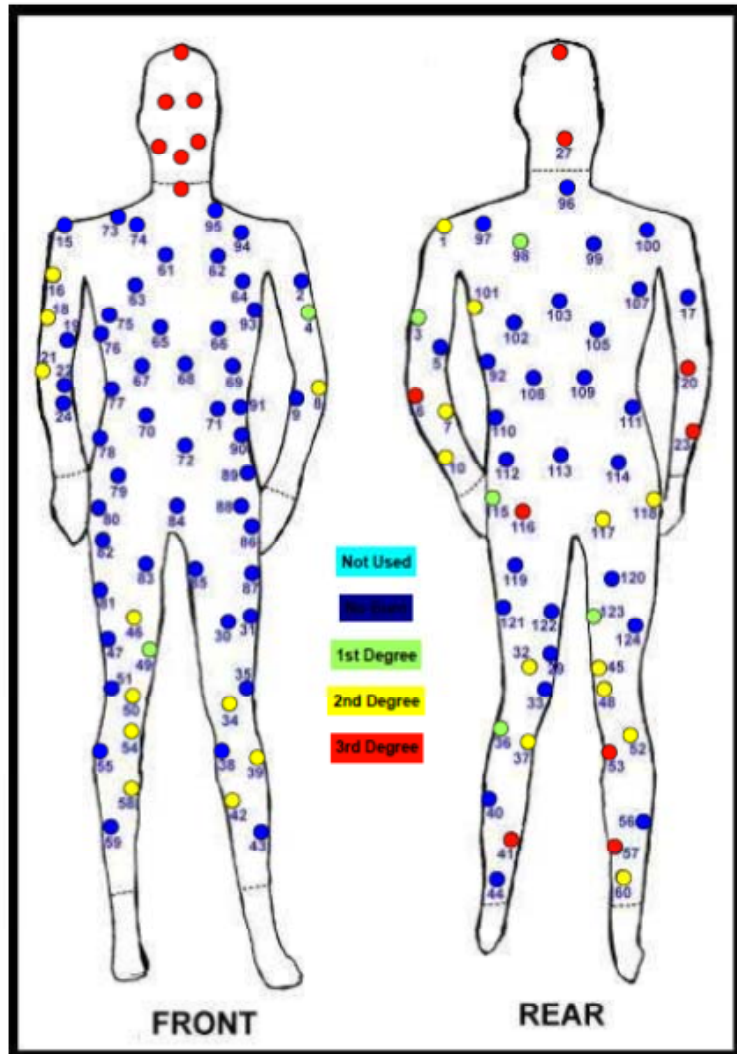Total (2nd&3rd): 34.53%

Model: ASTM1930 BurnModel 20130513.m

Figure C-9. Burn injury prediction: Defender M coveralls with UHMWPE 650D knit undergarments.

Burn Injury Prediction:
No Burn: 63.03%
1st Degree: 6.39%
2nd Degree: 15.41%
3rd Degree: 15.17%
Total (2nd&3rd): 30.58%
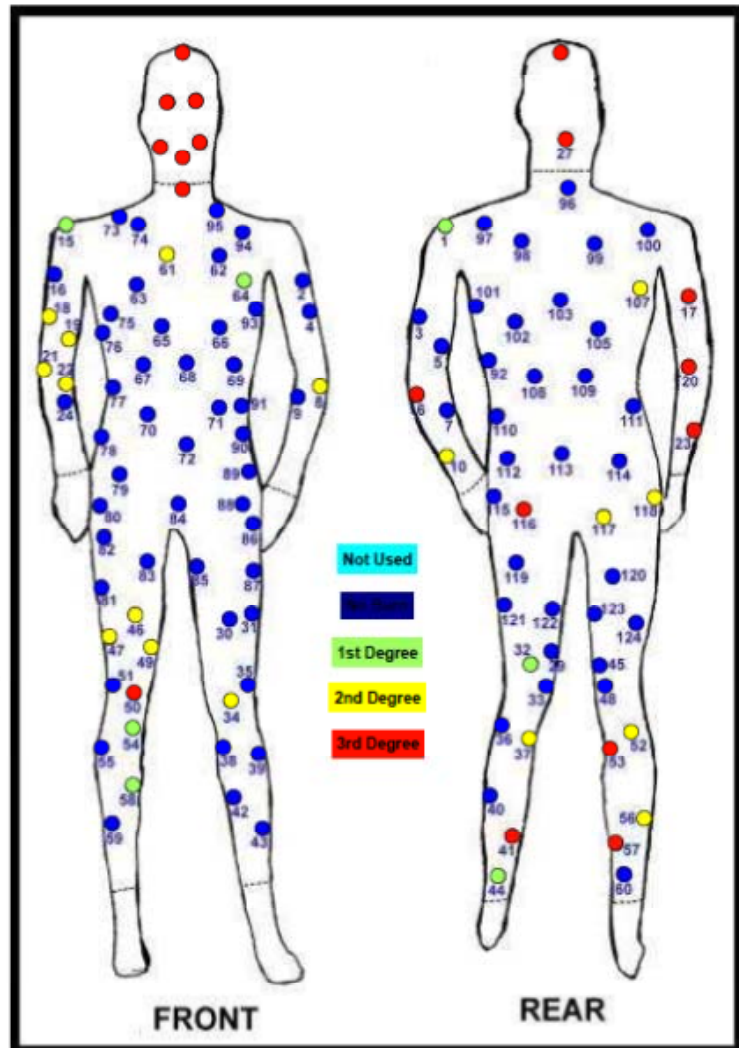
Model: ASTM1930 BurnModel 20130513.m

Figure C-10. Burn injury prediction: Defender M coveralls with UHMWPE 375D woven undergarments.